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Characteristics and Treatability of Urban Runoff Residuals

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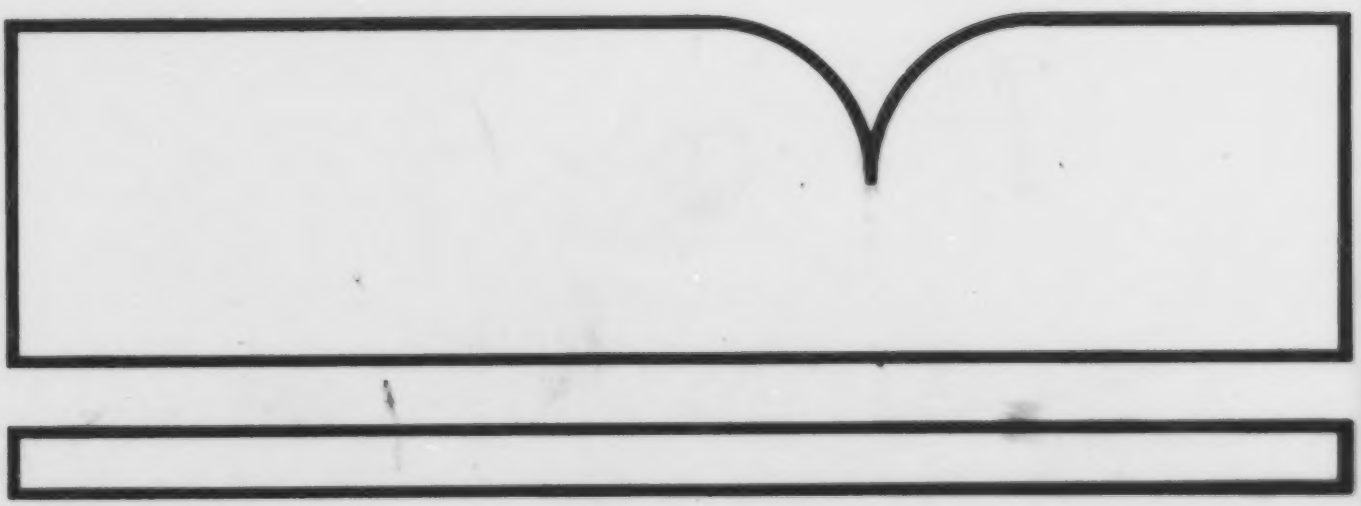

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CHARACTERISTICS AND TREATABILITY OF URBAN RUNOFF RESIDUALS

by

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16. ABSTRACT This study was undertaken to determine the character of urban stormwater runoff (UR) residuals as well as handling and disposal techniques. Samples of UR residuals for this study were obtained from a field-assembled sedimentation basin in Racine, WI, swirl and helical bend solids separators in Boston, MA, and an in-line upsized storm conduit in Lansing, MI. The characterization study included analyses for nine metals, eignt pesticidies and PCB's, solids, nutrients and organics. The treatability study included bench scale sedimentation tests, centrifugation tests, lime stabilization tests and capillary suction time tests.

The total solids concentration of the residual samples obtained from the three sites varied from 233 mg/1 to 161,000 mg/1. The concentration of nutrients (TKN, NH_3, NO_2, and NO_3) varied from 0.3 mg/1 to 2250 mg/1. Iron was found in the highest concentration (6.1 mg/1 to 2970 mg/1) of all the metals investigated, and the second and third highest concentrations observed were those for lead and zinc, respectively. PCB's were observed in measurable concentrations (0.19 µg/1 to 24.6 µg/1). Of the eight pesticides surveyed, only three (DDT, DDD and Dieldrin) were found in measurable concentrations.

Treatability data indicated that gravity thickening is a very effective means for dewatering UR residuals. Centrifugation was also found to be effective in thickening UR residuals. Stabilization using lime was recommended.

Based upon the study results, the most cost-effective UR residuals handling and disposal method is gravity thickening followed by landfilling.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Sludge Sedimentation Stormwater Sludge Disposal Thickening Dewatering Urban Runoff	Centrifugation Lime Stabilization Solids Separation	13 B

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development are necessary steps in problem solutio.; they involve defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to present and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

This report describes the results of a study designed to evaluate the characteristics, handling, and disposal of sludges produced in the treatment of urban stormwater runoff.

Francis T. Mayo, Director
Municipal Environmental
Research Laboratory

ABSTRACT

Studies have been undertaken to determine the characteristics, treatability and cost of handling and disposal of wastewater treatment plant and combined sewer overflow (CSO) sludges, but few have considered urban stormwater runoff residuals. This study was undertaken to determine the characteristics of urban stormwater runoff residuals as well as handling and disposal techniques.

Samples of urban stormwater runoff residuals for this study were obtained from a field-assembled sedimentation basin in Racine, Wisconsin, swirl and helical bend solids separators in Boston, Massachusetts, and an in-line upsized storm conduit in Lansing, Michigan. The drainage basins at each site were primarily residential in character. The residuals samples from Racine and Boston were obtained from individual stormwater events while the sample obtained from Lansing represented an accumulation of residuals from runoff events occurring over a six month time period.

The characterization study included analyses for nine metals, eight pesticides and PCB's, solids, nutrients and organics. The treatability study included bench scale sedimentation tests, centrifugation tests, lime stabilization tests and capillary suction time tests.

The total solids concentration of the residuals samples from Racine ranged from 233 mg/l to 793 mg/l (104 mg/l to 155 mg/l total volatile) while the residuals samples from Boston had a total solids concentration that ranged from 344 mg/l to 1,140 mg/l (107 mg/l to 310 mg/l total volatile). The residuals sample from Lansing, Michigan had a total solids concentration of 161,000 mg/l (25,800 mg/l volatile). The concentration of individual nutrients (total phosphorous, TKN, NH_3, NO_2 and NO_3) in the Boston and Racine samples never exceeded 5 mg/l, while the concentrations in the Lansing sample were between 0.3 mg/l and 2,250 mg/l. Of the metals, iron was found in the highest concentration in all the samples (6.1 mg/l to 2,970 mg/l), with lead and zinc ranking second and third, respectively. PCB's were observed in measurable concentrations (0.19 µg/l to 24.6 µg/l) in all samples except the October, 1980, Boston samples. Of the eight pesticides surveyed, only three (DDT, DDD and Dieldrin) were observed in measurable concentrations. However, the pesticides were primarly soluble while the PCB's were more related to the suspended solids.

Treatability data indicated that gravity thickening is a very effective method for thickening stormwater residuals. Solids recovery in the thickened residuals ranged from 46 to 94 percent in the Boston, Racine, and Lansing samples during one hour thickening tests. The solids concentration of the gravity thickened residuals ranged from 9 to 37 percent. Centrifugation, as expected, was also found to be an effective method for thickening the

stormwater runoff residuals. Solids recovery ranged from 77 to 99 percent. The quantity of lime required for stabilization of the stormwater runoff residuals varied from 1.2 to 6.6 grams CaO/liter.

Based on the results of this study, the most cost-effective treatment for handling and disposal of urban stormwater runoff residuals is gravity thickening followed by lime stabilization and landspreading or direct landfilling. Total annual cost estimates for landfilling and landspreading of residuals generated from a hypothetical 50 hectare site range from $360 to $470 per hectare.

The report was submitted in fulfillment of EPA Grant No. R-806785 by Marquette University and Rexnord Inc., Environmental Research Center under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period from October 4, 1979 to July 17, 1981. Work was completed as of August 14, 1981.

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The direction of this project by Mahendra Gupta and Anthony Geinopolos is also appreciated. Lastly the invaluable assistance of the Environmental Research Center personnel during sample collection and analysis is acknowledged with gratitude.

SECTION 1

INTRODUCTION

Controlling stormwater runoff from urban areas is a problem that some cities and towns will have to face in the future. One study (1) has shown that biochemical oxygen demand (BOD_5) and suspended solids (SS) from stormwater runoff represent 20 percent and 85 percent respectively, of the total BOD_5 and suspended solids input to the receiving streams. Another study (2) has shown that for some areas about 20 percent of the year (during runoff events) receiving stream quality is governed by stormwater runoff. The potential impact of urban runoff on receiving streams has prompted some communities to consider urban runoff control. A number of communities have already undertaken projects to mitigate the impact of urban runoff on rivers and lakes in their areas (3).

Many studies have been presented on the availability of nutrients (phosphorus and nitrogen compounds) (4) (5) (6) (7); the presence of pathogens (8); the presence of metals (9); and the presence of hydrocarbons (10) in the urban runoff.

Studies have also been performed on determining the impact of urban runoff on receiving waters (11, 12). These studies and others have presented the characteristics and pollution potential of urban runoff. Relatively little is known, however, of the characteristics, treatability, and disposal techniques for urban runoff residuals. The study conducted and reported herein breaks new ground by providing some of these data, namely: the characteristics and treatability of urban runoff residuals; cost estimates on treatment of urban runoff residuals; and, methodology for the ultimate disposal of the residuals from treatment.

PROJECT OBJECTIVES

The broad objective of this study is to provide data and pertinent information related to the characteristics, handling, and disposal of urban runoff treatment residuals. The objective was achieved by accomplishing the following:

1. Determination and selection of promising methods for treating urban runoff.
2. Characterization of the residuals generated from treatment of urban runoff.
3. Determination of the most feasible handling processes for the residuals from each treatment method.
4. Evaluation of the costs for handling and disposal of the residuals.

The data presented in this report were obtained from urban runoff treatment residuals collected from field test sites in Racine, Wisconsin; Lansing, Michigan; and Boston, Massachusetts.

The results of this study are presented in the following sections. Section 4 describes the promising urban runoff treatment methods, field site selection and the sampling, analytical, and treatability procedures used at the three sites. Section 5 discusses the results of the characterization of urban runoff residuals. The results of the bench-scale treatability studies are presented in Section 6. An evaluation of the costs of treating urban stormwater runoff residuals is presented in Section 7, and an overview of the project is presented in Section 8.

SECTION 2

CONCLUSIONS

1. Characteristics of raw stormwater runoff residuals.

   a. The volumes of residuals produced by the stormwater runoff treatment methods used varied from less than 1 to 12.6% of the raw flow volume treated.

   b. The residuals collected from the stormwater controls in Racine and Boston were relatively thin and dilute as evidenced from the total solids content which varied from 233 to 1140 mg/l.

      On the other hand, the residuals collected (after six months accumulation) from Lansing were relatively concentrated as evidenced by the total solids content of 161,000 mg/l.

      The wide range of residuals solids characteristics observed is attributed to the design and operation of the control method utilized. Moreover, the above observations indicate, as expected, that the residuals are amenable to concentrating by gravity thickening.

   c. The total volatile solids content of the residuals from the control methods sampled varied from 11 to 43%. These results indicate that stormwater residuals are more inert than municipal primary and activated sludges, whose volatile solids contents may vary from 70% to 85%.

   d. Pesticide and PCB concentrations in the residual sludges investigated were significant. Generally, the PCB concentrations were appreciably higher (40 to 1275 µg/kg dry) than those for the pesticides (3 to 90 µg/kg dry). Also, the PCB's were more associated with the solids than were the pesticides, which were predominately soluble in nature.

   e. Of the metals investigated, iron was by far the most abundant metal observed in the residuals analyzed, followed in the ranking by lead and zinc, respectively.

2. Dewatering of stormwater runoff residuals.

   a. The results of the bench scale gravity thickening tests showed that this dewatering method was effective for concentrating residual solids. The thin, dilute raw residuals (0.01 to 0.11%) obtained from Racine and Boston were concentrated to 9 to 19% content and the relatively concentrated raw residual (16% solids) from Lansing was further thickened by gravity to 37% solids content.

   b. Centrifugation was also found to be effective in concentrating runoff residuals. The results of the bench scale tests performed showed that the relatively thin, dilute residuals from Racine and Boston could be concentrated to cakes having solids concentrations up to 14%. The relatively concentrated raw residual from Lansing was further thickened by centrifugation to cake solids concentrations as high as 55%.

3. It was concluded that the cost-effective means for handling and disposal of urban stormwater runoff residuals is gravity thickening followed by lime stabilization and landspreading or direct landfilling.

SECTION 3

RECOMMENDATIONS

1. A pilot scale or full scale sedimentation/thickening facility of a similar design as presented in this report should be constructed. The design should include ancillary equipment that will enable the facility to serve as a research site for urban runoff residuals treatment.

2. The impact of landfilling and landspreading of urban runoff residuals should be evaluated. Special attention should be given to the accumulation and migration of pathogenic bacteria, heavy metals, and organochlorine compounds such as pesticides and PCB's.

3. A research program should be conducted evaluating the characteristics and treatability of urban runoff residuals in an area with an extensive street sweeping program, and the results compared to those found for this study, especially the economics of ultimate residuals management.

4. Studies should be conducted to determine the optimum disposal techniques for the liquid effluent from thickening of urban runoff residuals since this effluent is the primary source of pesticides associated with the residuals.

SECTION 4

SITE SELECTION, SAMPLING, ANALYTICAL, AND TREATABILITY PROCEDURES

SELECTION OF RESIDUALS TREATMENT PROCESSES

Solutions to the urban runoff (UR) pollution problem can be grouped as follows:

1. Source control.
2. Treatment.

Source control techniques involve non-structual approaches and include land use restrictions, erosion control practices, and street, catch basin and sewer cleaning. Treatment options include:

1. Storage/sedimentation.
2. Sedimentation/chemical clarification.
3. Microscreening.
4. Screening/dissolved-air flotation.
5. Filtration.
6. Swirl concentration.
7. Helical Bend solids separation.

A recent study (13) indicated that treatment processes 2, 3, 4, and 5, above, require some type of preliminary storage/sedimentation to dampen the variable flow associated with urban runoff to allow them to operate at higher solids removal efficiencies. Therefore, these processes were deemed to be relatively costly, sophisticated polishing steps following storage sedimentation that would not likely find widespread use. In view of this, the residuals investigated in this project, were reduced to those produced by treatment methods 1, 6 and 7, above. Source control techniques were not evaluated in this study.

SITE SELECTION AND SAMPLING PROCEDURES

In contrast to the treatment of combined sewer overflow (CSO), where full-scale operating control facilities exist, a paucity of information was available regarding full-scale operating stormwater control facilities at which residue samples could be obtained for characterization and study for treatment and disposal. This made it difficult to locate potential candidate sites for this study.

Storage/Sedimentation

One of the first tasks of this study was to locate facilities or sites which received stormwater runoff and were amenable to obtaining samples of stormwater runoff residuals. A review of stormwater runoff control case histories presented in "Urban Stormwater Management and Technology" (3) and discussions with other sources (such as the Southeastern Wisconsin Regional Planning Commission, City of Racine, Wisconsin Department of Natural Resources and Metropolitan Sanitary District of Greater Chicago) produced an inventory of potential sites using storage/sedimentation for control of stormwater runoff.

Six sites were selected from this list and their characteristics compared. The six sites are: The Woodlands, Texas; Orange County, Florida; Montgomery County, Maryland; Racine, Wisconsin; Franklin, Wisconsin; and Lansing, Michigan. The review of these sites indicated that stormwater runoff detention basins could be divided into two groups: wet detention ponds and dry detention ponds.

Wet detention ponds are sites that are filled with water for the duration of the rainy season or throughout the year. The stormwater runoff control facility at the Woodlands, Texas, is an example of a wet detention pond. Two major lakes at the site are used to reduce runoff peak flows and to trap sediment in the stormwater runoff. It was determined that the usual wet detention pond encountered would not be appropriate for this study. The residuals generated would not be representative because:

1. Of the difficulty of distinguishing between residuals associated with the urban runoff and those residuals indigenous to the pond.
2. Most of the stormwater is transported overland, thereby reducing the quantity and quality of the runoff residuals.
3. Of degradation of the residuals during long storage.
4. Of the accumulation between storms.

It was determined that this type of wet detention pond would be very difficult to sample for stormwater runoff residuals, and thus, this type of system was eliminated from further consideration. Further, the original

intent of the project was to consider only residuals generated from actual stormwater treatment devices rather than from stormwater runoff management systems.

However, a variation of the wet detention pond at Lansing, Michigan was reviewed and it was determined that because of its uniqueness, this particular site would provide satisfactory samples of stormwater runoff residuals. This system uses an enlarged storm sewer to accumulate stormwater runoff residuals and sample collection was determined to be straightforward. A description of the facility is presented later in this section.

The second type of stormwater runoff control facility is a dry detention pond. These facilities fill with stormwater runoff during a storm and the runoff subsequently drains from the pond through relatively small effluent lines (effluent storm lines are sized smaller than the influent lines to promote storing of the runoff in the detention pond for a short period of time for percolation into the ground or evaporation from the detention site). One of the facilities at Orange County, Florida, uses a percolation pond, wherein only the first flush is diverted and stored.

Montgomery County, Maryland has wet and dry detention ponds which function as described above. Unfortunately, the greatest problem associated with using any of these sites was collection of samples and shipment back to the Environmental Research Center (ERC) for characterization and treatability studies. As a result, local sources (Southeastern Wisconsin Regional Planning Commission, City of Racine and Wisconsin Department of Natural Resources) were contacted and local potential sites were discussed and considered. The two most feasible sites identified were at Franklin, Wisconsin and Racine, Wisconsin.

The Franklin site consisted of a small dry detention pond that also served as a sandlot baseball field. Unfortunately, stormwater runoff to the site travels over ground and it was expected that some of the solids from the runoff area could be expected to be trapped in the grass growing on the slopes around the detention pond.

The next area reviewed was Racine, Wisconsin. Five detention ponds, three dry ponds and two wet ponds, were visited and it was determined that one site, a dry retention pond located off Bird Avenue, would be satisfactory for this study.

This site, Figure 1, was originally designed to reduce the stormwater runoff flowrate from the western edges of the city. Because the city was expanding westward, the storm sewers to Lake Michigan were forced to carry larger volumes of stormwater runoff. The results were wide areas of flooding during heavy rainfalls. The detention ponds in Racine were built to reduce the rate of stormwater runoff flow in the sewer lines. This was accomplished by putting relatively small sized effluent lines in the detention basin. Then, for example, stormwater volumes that would normally run off in 30 minutes would take 60 to 90 minutes. The storm sewers

Figure 1. Urban runoff detention pond in Racine, WI.

would then be running at peak capacity for longer periods of time, but they would not be overloaded. The Bird Avenue detention pond serves a 29.3 hectare (72.3 acres) drainage area. Figure 2 shows the boundaries of the drainage basin area and outlines the land use zones (R-2 is single family residence; R-4 is general residence; and O/I is office/institutional).

The detention pond is located in the northeast corner of the drainage basin. Stormwater runoff is carried to the pond by a 1.22 m by 1.52 m (48 in. by 60 in.) eliptical storm sewer. A sedimentation chamber was constructed to facilitate the collection of the residuals from a storm event and to prevent the adverse effect on residuals' quality which may have been brought about by percolation into the site soil and by overland passage through high grass. Residuals in the stormwater runoff were collected by building a 6.1 m by 24.4 m (20 ft by 80 ft) sedimentation basin. The sedimentation basin was constructed with 10 mil polypropylene sheeting, sandbags, and 2 in. by 4 in. lumber. The position of the sedimentation basin within the detention pond is illustrated in Figure 3 (also shownin Figure 1). Stormwater entered the south end of the sedimentation basin and then overflowed at the north end. The north end of the basin was built up to a height of 60 cm (24 in.) with the east and west edges being built up to the same elevation. Figure 4 shows how the sedimentation basin was assembled in the detention pond.

The sedimentation basin was assembled on site prior to the storm event. Stormwater runoff fills the basin and overflows at the north end. The detention time in the basin depends on the rate of runoff and thus the amount of settling that occurs will vary. Samples of the influent and effluent were obtained on a flow basis throughout the runoff event. Influent flow rate was calculated utilizing actual sewer flow depth, physical sewer characteristics and Manning's formula.

After the runoff from the storm event decreased significantly, the inlet to the sedimentation basin was blocked and the runoff that was in the basin was allowed to settle for one hour. At the end of the settling phase the level of the runoff in the basin was gradually reduced by draining the supernatant. The remaining residuals were then collected and returned to the Environmental Research Center for characterization analyses and treatability studies.

At the Lansing, Michigan test site, an assessment of two in-line urban stormwater best management practices (BMP's), an in-line wet retention basin and two in-line upsized pipes, is being undertaken pursuant to the goals of the United States Environmental Protection Agency (USEPA) Nationwide Urban Runoff Program (NURP) (20). The study is being conducted to determine the operational costs and effectiveness of the two types of BMP's in the enhancement of the quality of storm generated runoff.

The Lansing, Michigan site was of interest to the study reported herein in that in-line BMP's within a drainage network provide a central location

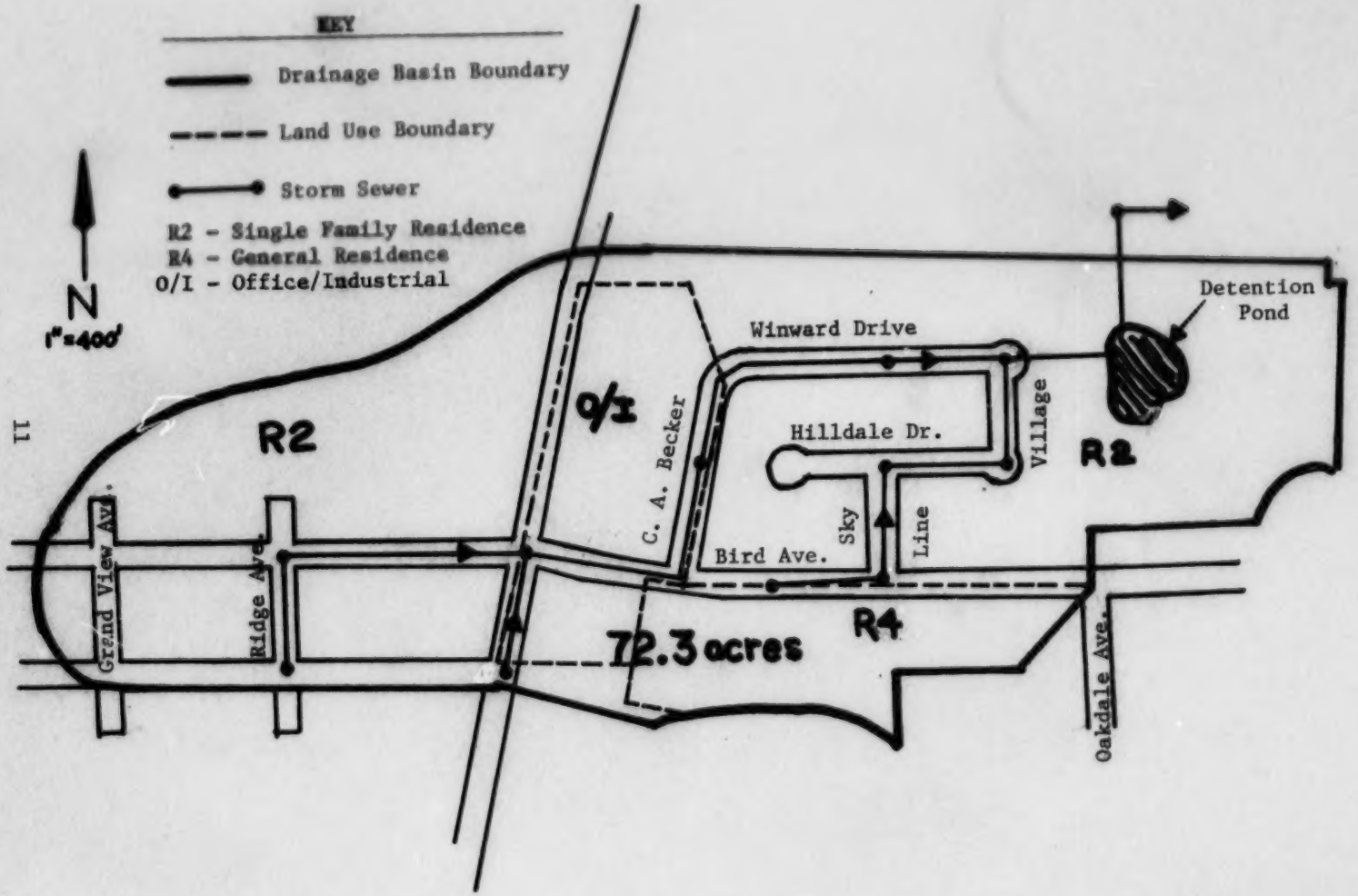

Figure 2. Zoning map for the drainage basin served by the stormwater runoff detention basin on Bird Ave., Racine, WI.

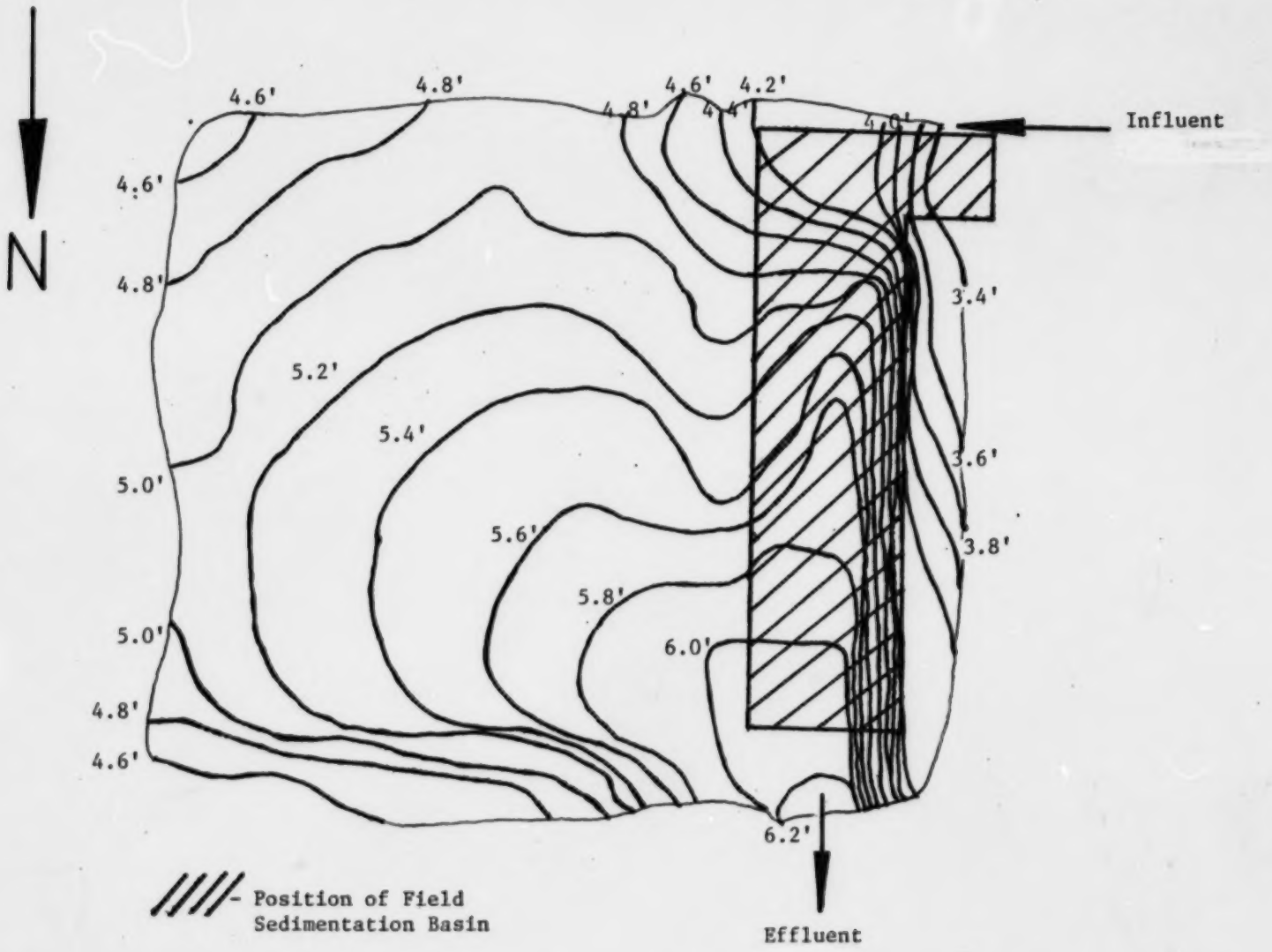

Figure 3. Topographic map for northwest corner of Bird Avenue stormwater detention pond. Elevations give feet below benchmark. Scale 1 cm = 2.4 meters.

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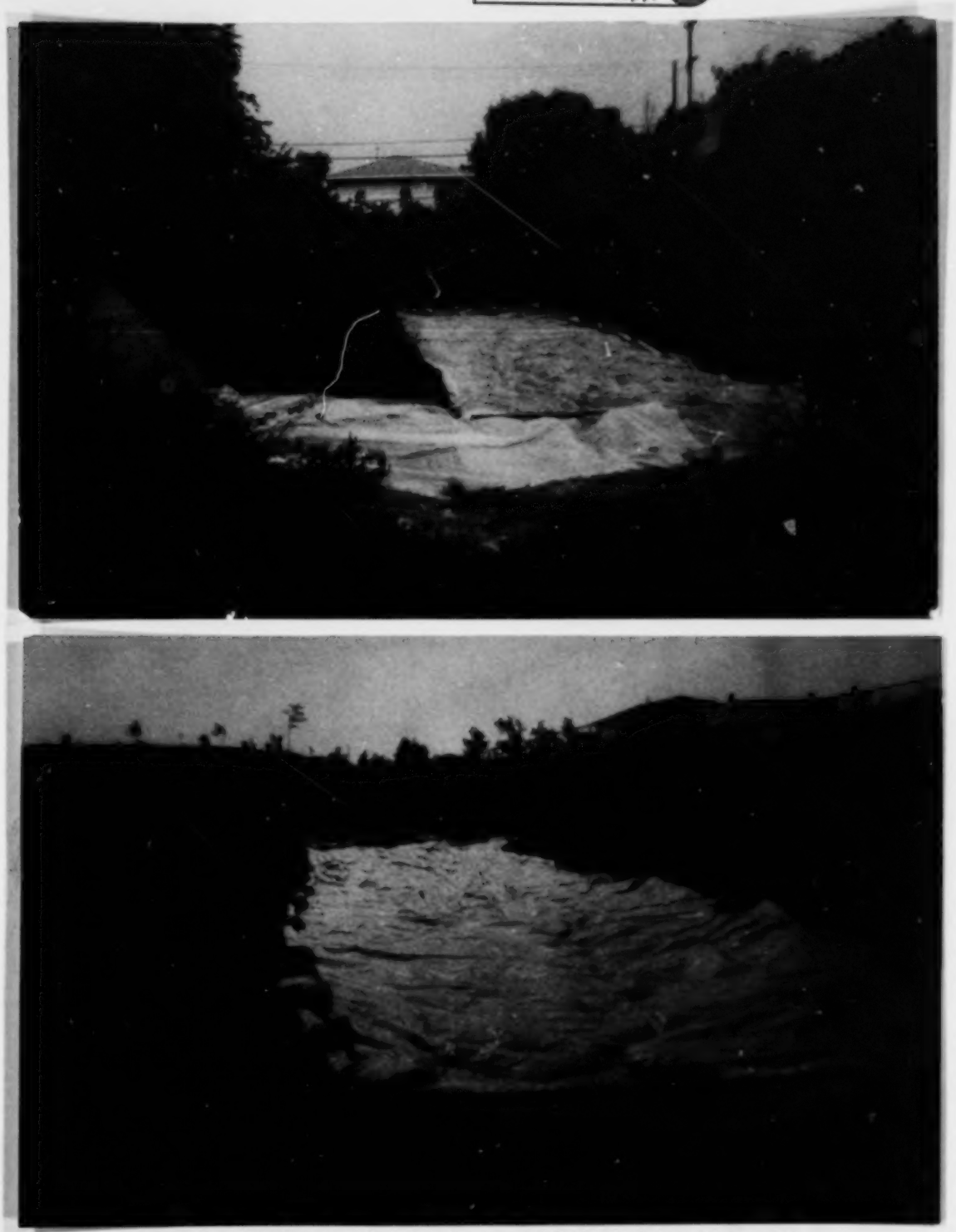


Figure 4. Sedimentation basin assembled in detention pond.

where the velocity of stormwater would be slowed, allowing for deposition of solids and subsequent periodic removal.

For the study reported herein, samples of the residuals from one of the in-line upsized pipes at Lansing were obtained for characterization and treatability studies. In Figure 5 are shown the locations of the in-line upsize pipes and the outlines of the sub-basins draining through the upsized pipes. It should be noted that the north upsized pipe (Figure 5) receives "treated" water from the south upsized pipe.

The south upsized pipe (Figure 5) was selected for investigation. This upsized pipe receives drainage from 31.6 hectares (78.0 acres) of mixed residential (50 percent), industrial (20 percent) and public (30 percent) land uses. The upsized pipe was in-line, constructed of 2.4 meters (96-inch) diameter reinforced concrete, with crown elevations the same as the inlet and outlet pipes. The inlet and outlet pipe diameters were 1.2 and 1.4 meters (48 and 54 inches), respectively. The south upsized pipe had a length of 43.9 meters (144 feet) at a 0.8 percent slope, which provided an average standing water depth of 1.1 meters (42 inches) and a capacity of 70.8 cubic meters (2500 cubic feet). Figure 6 illustrates the upsized storm sewer and the inlet and outlet pipes.

Samples from the upsized storm sewer were collected after the system had been in operation for approximately six months during 1980. Figure 7 shows how the samples were collected from the upsized sewer. Five-gallon containers were used to scoop up equal volumes of runoff residuals along the length of the conduit. The samples were then transported back to ERC for characterization analyses and treatability studies.

Swirl and Helical Bend Solids Separators

The Boston, Massachusetts stormwater runoff treatment site is an EPA pilot project for the swirl and helical bend solids concentrators (15). Figure 8 shows the drainage basin boundaries for the Boston site. The total area drained is 65 hectares (160 acres) with essentially all of it being low density residential.

The swirl solids concentrator uses a swirl action to separate grit, settleable matter, and floatable solids at a fraction of the detention time normally required in sedimentation.

The helical bend separator uses the same mechanism of solids/liquid separation as the swirl concentrator.

The principle behind its effectiveness is helical motion which is developed in fluids at bends when a total angle of 60 degrees and a radius of curvature equal to 16 times the inlet pipe diameter is used. Sketches of both solids concentrators are shown in Figure 9. The particulars relevant to the swirl and helical bend solids concentrators used in the Boston demonstration project are given on the following page.

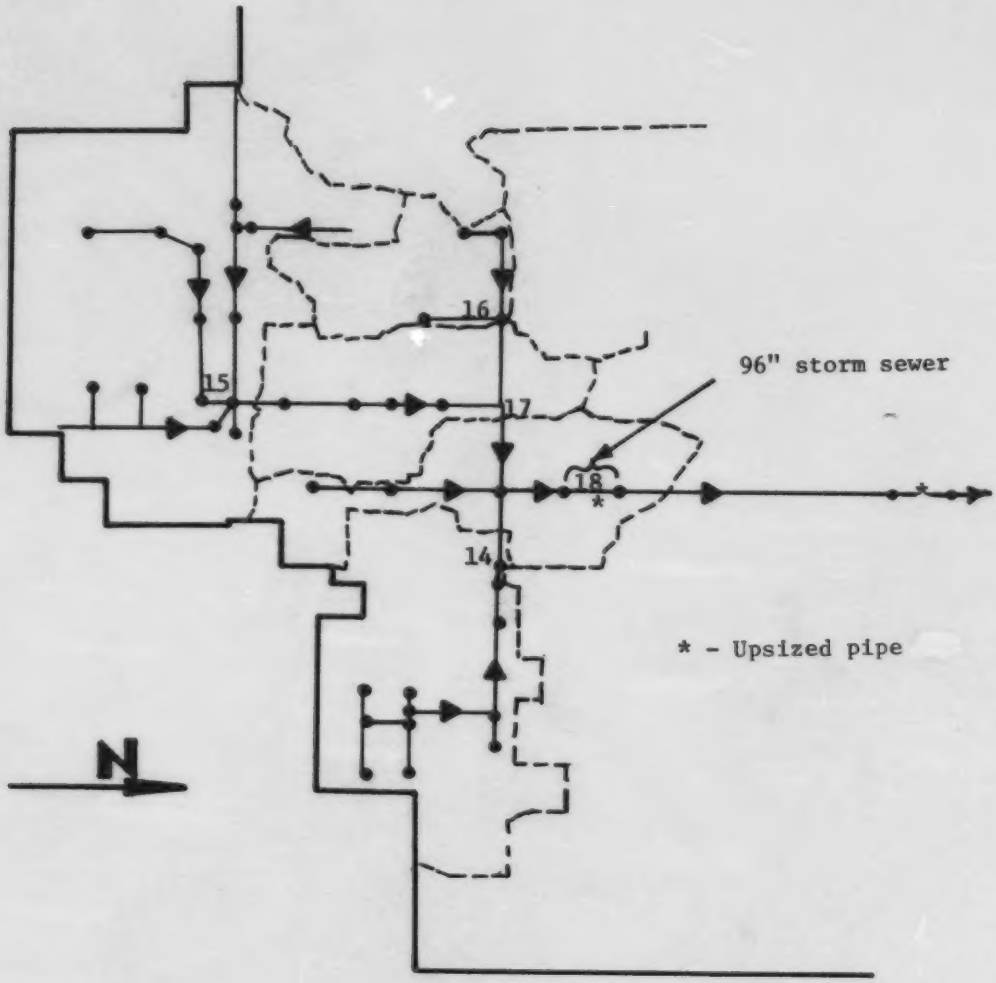


Figure 5. Drainage basin map for upsized storm sewer in Lansing, Michigan. The sub-basins draining through the upsized tile are numbers 14, 15, 16, 17, and 18. The 96 inch storm sewer is located in sub-basin 18.

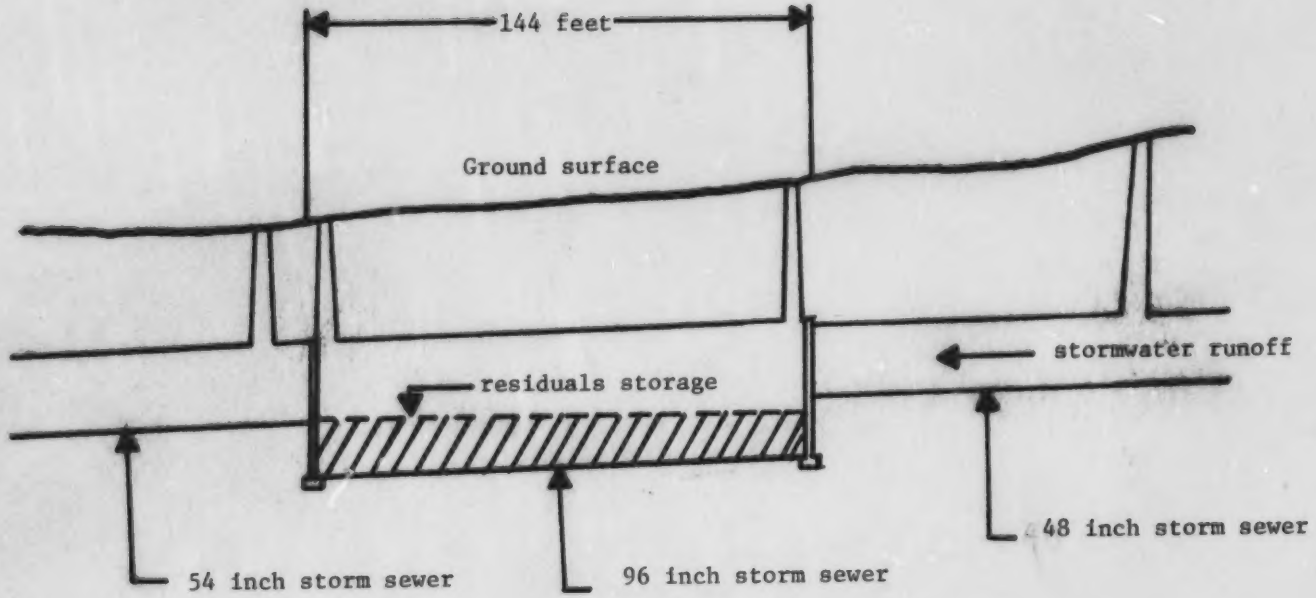


Figure 6. Position of upsized storm sewer in Lansing, Michigan, stormwater drainage system.

Figure 7. Interior of upsized storm sewer in Lansing, MI. Highwater marks (A) show level of supernatant before pump down. Remaining material is thickened residuals (B).

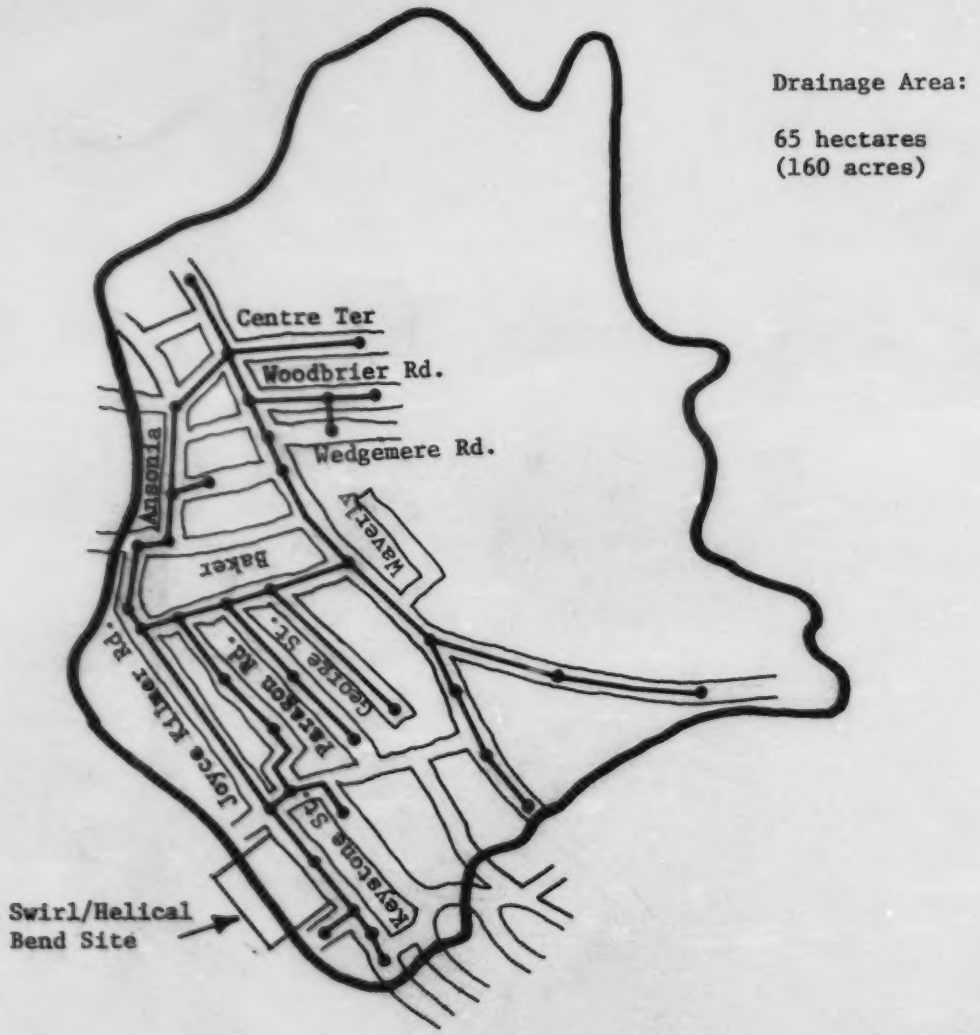
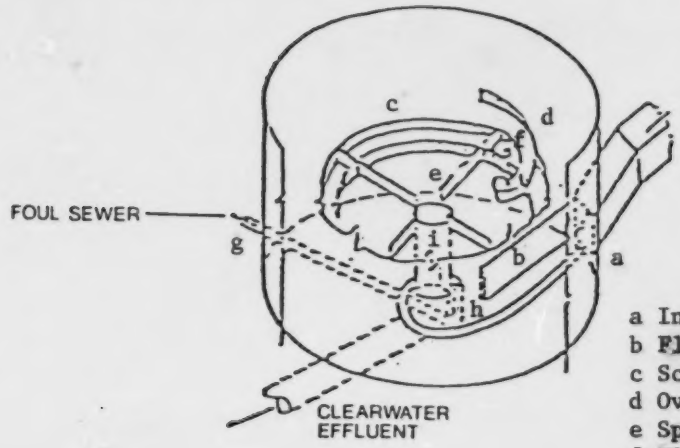
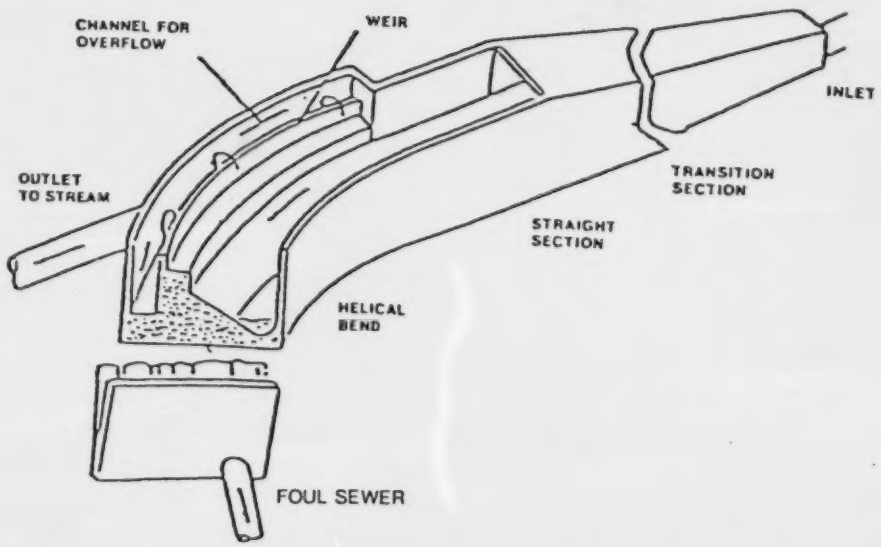


Figure 8. Drainage basin boundary for helical bend and swirl solids separator test facility.



A. SWIRL

a Inlet Ramp
b Flow Deflector
c Scum Ring
d Overflow Weir & Weir Plate
e Spoilers
f Floatables Trap
g Foul Sewer Outlet
h Floor Gutters
i Downshaft



B. HELICAL BEND

Figure 9. Cut-away view of swirl and helical bend solids separators.

1. Swirl concentrator

    a. Design flow - 0.17 cms (6 cfs)
    b. Peak flow - 0.34 cms (12 cfs)
    c. Diameter - 3.20 m (10 ft - 6 in)
    d. Depth - 1.83 m (6 ft)

2. Helical bend solids concentrator

    a. Design flow - 0.17 cms (6 cfs)
    b. Peak flow - 0.34 cms (12 cfs)
    c. Length - 19.83 m (65 ft)
    d. Depth - 1.22 m (4 ft)

Separate samples of the underflow (concentrated influent) from each device were collected following a selected stormwater event. Sample collection and shipment were accomplished by the firm responsible for conducting the studies on the Boston demonstration project for the EPA.

Samples were collected in four 15 liter (4 gallon) carboys and shipped to the ERC laboratory for treatability tests and for selected analyses. In addition, samples for characterization were collected in one-gallon sterile glass bottles and similarly shipped. All samples were shipped via air freight (one day service).

Samples collected in the sterile glass bottles were first analyzed for fecal coliforms and fecal streptococcus. The remaining sample contents were then analyzed for PCB and chlorinated hydrocarbons.

A portion of the carboy samples were taken, split into four aliquots and preserved as follows for the constituent analyses noted below.

1. No preservative - For total solids, suspended solids, BOD and total dissolved solids.

2. Sulfuric acid preservation (1 ml of 1:1 H_2SO_4/250 ml of sample) - For COD, TOC, total P, TKN, NH_3 and NO_3/NO_2.

3. Sulfuric acid preservation to pH of 2 - For oil and grease.

4. Nitric acid preservation to pH of 2 - For metals (Hg, As, Pb, Zn, Fe, Cu, Ni, Cr and Cd).

ANALYTICAL PROCEDURES

Analytical procedures were conducted in accordance with Standard Methods for the Examination of Water and Wastewater (16). Details are presented in Appendix A.

TREATABILITY TEST PROCEDURES

The bench scale treatability tests consisted of gravity thickening, centrifuge dewatering, buchner funnel test, capillary suction time test, and lime stabilization. Appendix B contains detailed descriptions of the treatability test procedures. A brief description of these tests is presented below:

1. Gravity Thickening

These tests were conducted in one liter graduated cylinders. The cylinders were filled with stormwater runoff residuals to the 1,000 ml mark and allowed to settle for one hour. The residuals samples from Racine and Boston were dilute suspensions and no zone settling was observed. Discrete particles were then monitored to determine settling characteristics of the samples. Design parameters were based on these observations. The residuals sample from Lansing did exhibit zone settling. The data derived was then analyzed by the method developed by Talmadge and Fitch (17).

2. Centrifuge Dewatering

Stormwater runoff residuals were centrifuged (160 ml samples) for various times at different gravitational forces. The resultant centrate was decanted and analyzed for volatile suspended and suspended solids. Centrifuged cake solids, residuals cake quantity, and optimum spin time and spread were determined.

3. Lime Stabilization

Bench scale laboratory tests were conducted to determine the quantity of lime (CaO) required to raise the pH of thickened and unthickened residuals to a specific level. The quantity of lime required was found in a previous study to be dependent on the chemical characteristics and solids concentration of the runoff residuals (18).

4. Capillary Suction Time Test (CST)

A ten milliliter sample of stormwater runoff residuals is placed in an open bottom cylinder positioned in the center of an absorbent pad. As the water is drawn outward by capillarity, a clock times the movement of the water over a specified distance. The resulting capillary suction time is then a measure of the dewaterability of the sample.

5. Buchner Funnel Test

Aliquots of residuals from the Lansing, Michigan site were filtered through a Whatman No. 4 filter paper held in a Buchner funnel. The

volume of filtrate and elapsed time were recorded as the test progressed. The specific resistance of the residuals cake was then calculated from these data. The specific resistance is used to predict the need for conditioning chemicals in the dewatering of UR treatment residuals.

SECTION 5

CHARACTERIZATION OF URBAN RUNOFF RESIDUALS

The characterization of stormwater runoff residuals is presented according to the following test sites and the type of treatment processes utilized at the various sites.

A. Racine, Wisconsin Site

1. Storage/settling
2. Field assembled settling basin
3. Single storm treatment

B. Lansing, Michigan Site

1. Storage/settling
2. In-line upsized storm sewer
3. Multiple storm treatment

C. Boston, Massachusetts Site

1. Physical treatment
2. Swirl solids separator
3. Helical bend solids separator
4. Single storm treatment

A discussion of the volume of residuals produced in each group and the residuals characteristics is presented in the following sections. The stormwater runoff residuals quality data are based on composite samples for the above three sites. Stormwater runoff residuals quantity data are based on treatability test results and estimates of runoff coefficients for each drainage basin (Table 1).

STORMWATER RUNOFF RESIDUALS VOLUME

The stormwater runoff produced per storm at each site and the estimated volume of residuals from the treatment of this runoff are presented in Table 1. The runoff coefficient of 0.5 shown in Table 1 was estimated

TABLE 1. STORMWATER RUNOFF FROM MONITORED STORMS AND THE ESTIMATED VOLUME OF RESIDUALS FROM EACH SITE STUDIED.

Site	Treatment	Drainage basin area, hectares	Estimated runoff coefficient	Date of Event	Rainfall cm	Antecedent Dry Days	Runoff volume sampled, m^3	Volume stormwater runoff residuals, m^3	Volume settleable solids[a] liters/m^3	Solids concentration of settleable solids, %
Racine, WI	Settling basin	29.3	0.5	6/28/80	1.2	7	1460	6[b]	2	10
				9/9/80	1.3	3	1230	14[b]	6	9
Lansing, MI	Upsized storm sewer	32.4	0.5		-			71[c]	590	37
Boston, MA	Swirl	64.9	0.5	10/25/80	2.5	7	319	33	0.6	14
	Helical Bend					7	119	15	0.3	19
	Swirl	64.9	0.5	6/23/81	1.0		130	5	3.5	15
	Helical Bend						424	30	2.2	15

[a]Volume settleable solids per m^3 stormwater runoff residuals.

[b]Volume retained for one hour settling in field basin.

[c]Volume is fixed by storm sewer sump.

Conversions: 2.47 acres = 1 hectare
264.2 gal. = 1 m^3
0.26 gal. = 1 liter

based upon the socioeconomic characteristics of the site drainage areas (21). The quantities of rainfall for each event at the Racine site were almost identical. The June 28, 1980, runoff event had 1.2 cm (0.47 in.) of rainfall, and the September 9, 1980 runoff event had 1.3 cm (0.5 in.) of rainfall. However, the intensity of each storm was quite different. The June 28 rainfall occurred over a 3-hour period, while the September 9 rainfall occurred over only 1.5 hours. This difference in intensity is one of the major reasons for the increase in the amount of settleable solids from 2 liters/m^3 in the June 28 runoff compared to 6 liters/m^3 in the September 9 runoff event. The solids concentrations in the settleable fractions were 10 percent and 9 percent, respectively. Another major reason for the increase in settleable solids is that the field assembled sedimentation basin was not in position during the first half hour of the June event, thus the first flush (which carries a relatively high solids load) was missed. The sedimentation basin was in position prior to the September runoff event and the first flush was routed through the field assembled basin. More of the runoff from the September event was also retained for settling. The volume of runoff retained for settling during the September event was 14 m^3, (495 ft^3) while only 6 m^3 (212 ft^3) were retained for settling in the June event.

The Lansing site in many ways functions in a similar manner as a wet detention pond. Suspended solids are removed by sedimentation from the runoff during a storm event and the solids are thickened while stored in the sump between events. The conduit sump will retain 70.8 m^3, (2501.7 ft^3) of runoff. The conditions in the sump are ideal for thickening. The volume of settleable solids in the residual sludge after the supernatant in the sump was pumped out was found to be 590 liters/m^3. The average concentration of solids in the settleable fraction was 37 percent.

The swirl and helical bend solids separators are pilot scale models and thus only treated a fraction of the total runoff from the drainage basin. Table 2 shows the influent and effluent flow rates from each unit during the sample composite period. The foul effluent (stormwater runoff residuals) was 10 to 16 percent of the swirl influent and 8 to 17 percent of the helical bend influent during the October 25, 1980, event. For the June 23, 1981 event the foul effluent from the swirl was 12 to 22 percent of the influent, and 3 to 19 percent of the helical bend influent.

From Table 1, for the October, 1980 storm event, the volume of settleable solids in the foul effluents from the swirl and helical bend units was 0.6 liters/m^3 and 0.3 liters/m^3 respectively. The concentration of solids in the settleable solids was 14 and 19 percent, respectively. For the June, 1981 event the volume of foul effluent settleable solids for the swirl unit was 3.5 liters/m^3 and 2.2 liters/m^3 from the helical bend. The concentration of solids in the settleable solids was 15 percent from both units.

TABLE 2. HELICAL BEND AND SWIRL SOLIDS SEPARATOR FLOW RATES* DURING SAMPLING. (Flows are given in liters per second)

October 25, 1980 Storm Event									
Swirl	Sampling Time, min.	26	37	82	86	89	92	95	100
	Influent	24	55	81	113	107	108	110	109
	Foul Effluent	-	5	13	13	13	13	14	14
	Clear Effluent	24	50	68	100	94	95	96	95
Helical Bend	Sampling Time, min.	-	37	47	52	56	59	61	63
	Influent	-	55	59	64	90	116	120	121
	Foul Effluent	-	9	10	-	-	10	-	10
	Clear Effluent	-	46	49	-	-	106	-	111
June 23, 1981 Storm Event									
Swirl	Sampling Time, min.	3	7	15	19	26	30	38	60
	Influent	77	65	51	57	59	54	42	-
	Foul Effluent	14	8	11	9	8	9	-	0
	Clear Effluent	62	57	40	48	51	45	-	-
Helical Bend	Sampling Time, min.	5	12	19	28	38	48	58	-
	Influent	164	283	275	218	150	65	42	-
	Foul Effluent	8	8	9	9	11	11	8	-
	Clear Effluent	156	271	266	209	130	54	34	-

* Data courtesy of Environmental Design and Planning, Inc., Cambridge Massachusetts.

gal/min x 0.0631 = liters/second

STORMWATER RUNOFF RESIDUALS CHARACTERISTICS

The stormwater runoff residuals samples collected from Racine and Boston were collected from pilot scale treatment systems. This was necessary, as previously mentioned, because of the paucity of full scale operation stormwater treatment facilities. The Racine samples were collected using a field assembled sedimentation basin that was large enough to contain several thousand gallons of runoff, but did not have a sufficient retention volume to provide adequate settling time for all the stormwater in a single storm event. The turbulence associated with the runoff and the high flow rate worked against any substantial solids capture. A mass balance during the September 9, 1980, event indicated that very little settling occurred. The average stormwater influent concentration was 56 mg/l while the effluent was 58 mg/l. Most of the residuals that were captured for characterization and treatability tests were from the several thousand gallons of stormwater runoff that was held in the basin for one hour after the influent to the basin was blocked. Decanting of the supernatant provided a relatively concentrated sample of urban runoff residuals.

The suspended solids concentrations in the influents and effluents of the swirl and helical bend systems in Boston are presented in Table 3. Table 3 contains a preponderance of data which shows that the swirl and helical bend separators were ineffective during this investigation in removing suspended solids from the influent flow. For example, in 18 of the 29 sets of Table 3 data from which this conclusion is drawn, the suspended solids content of the clear effluent flow approached or exceeded that of the influent flow. Moreover, note in Table 3 the relatively dilute nature of the foul effluent flow. In most cases, 22 of 29 sets of Table 3 data examined, the foul effluent suspended solids content approaches or is less than that in the influent flow.

Further investigation indicated that there was no readily apparent explanation for the ineffectiveness of the helical bend and swirl separators in removing suspended solids from the influent flow. For example, it may be remembered that the design flow rate for each of the two separators was 170 liters/sec (6 cfs or 2700 gpm). Examination of Table 2 shows that, for the swirl separator on both the October 25, 1980 and June 23, 1981 storm events, the influent flow rate to the swirl separator was well below the design flow rate. Similarly, the actual flow rates for the helical bend separator on October 25, 1980 were well below the design flow rate. On the other hand, the actual flow rate to the helical bend separator exceeded the design flow rate for a short period of time during the June 23, 1981 storm event, however, the actual flow rate was well below the design peak flow rate of 341 liters/sec (12 cfs or 5400 gpm). It is concluded, therefore, that the ineffectiveness of the swirl and helical bend separators to remove suspended solids from the influent storm flow was not flow rate related.

TABLE 3. SOLIDS CAPTURE DATA FOR SWIRL AND HELICAL BEND SOLIDS SEPARATORS*, ALL CONCENTRATIONS ARE GIVEN IN MG/L SUSPENDED SOLIDS.

	October 25, 1980 Storm Event								
Swirl		Sampling Time, min.	26	37	82	86	89	92	95	100
		Influent	153	44	174	170	185	168	118	141
		Foul Effluent	205	466	174	165	146	142	121	119
		Clear Effluent	24	102	184	183	133	165	165	138
Helical Bend		Sampling Time, min.	26	37	47	52	56	59	61	63
		Influent	22	144	240	177	165	160	403	141
		Foul Effluent	223	216	188	170	155	158	148	158
		Clear Effluent	63	76	225	181	165	150	148	154
	June 23, 1981 Storm Event									
Swirl		Sampling Time, min.	3	7	15	19	26	30	38	60
		Influent	743	614	408	498	384	800	1340	-
		Foul Effluent	752	697	424	285	392	462	872	1218
		Clear Effluent	740	573	427	374	328	484	-	-
Helical Bend		Sampling Time, min.	5	12	19	28	38	48	58	70
		Influent	268	449	433	456	480	331	485	-
		Foul Effluent	416	437	458	504	772	352	487	2427
		Clear Effluent	279	552	456	399	645	844	246	-

* Data provided courtesy of Environmental Design and Planning, Inc., Cambridge, Massachusetts.

The procedures used for collecting residuals from the Lansing site were previously described in Section 4. The residuals were a composite of solids that had accumulated over a six month period. As mentioned previously, at the Lansing site, an upsized pipe was investigated where the velocity of stormwater is slowed, allowing for deposition of solids and subsequent periodic removal. It would be expected that solids deposition would occur more readily during small storm events when increased detention time was provided and that performance might deteriorate during larger storm events. This hypothesis appears to have been borne out at the Lansing south upsize pipe (20). For example, for nine storm events monitored, 30-55 percent solids capture was estimated for the first five storms monitored which had rainfalls ranging from 0.56 to 1.6 cm (0.22 to 0.63 inches). For the subsequent four storm events where the rainfalls ranged from 1.09 to 4.14 cm (0.43 to 1.63 inches), deterioration of solids capture performance was indicated. It is speculated that the deteriorated performance was caused by the subsequent larger storms and/or by resuspension (scouring) of the deposited solids accumulated from previous storms.

The characteristics of all the stormwater runoff residuals obtained in this study are presented in Tables 4 to 10. The data in these tables are presented in terms of total concentration (mg/1) or (µg/1), soluble concentration (mg/1) or (µg/1) and (mg/kg) or (µg/kg) dry suspended solids. The total concentration is the measure of dissolved and undissolved fractions. The dissolved or soluble fraction of pesticides was obtained by centrifuging a sample at 3,000 g's for ten minutes and analyzing the centrate. The soluble fractions of all other parameters was obtained by filtering the sample through 0.45 µ filter media. The difference between the soluble concentration and total concentration is assumed to be associated with the suspended solids.

The residuals samples obtained in this study may be divided into two groups. The samples obtained from Racine and Boston are from single storm events. The sample from Lansing is from multiple storm events. The total solids concentration in the Boston and Racine samples ranged from 233 to 793 mg/1, while the Lansing sample had a total solids concentration of 161,000 mg/1 and suspended solids concentration of 159,900 mg/1.

The volatile fraction of the total solids in the samples ranged from 11 percent to 67 percent. The high and low levels occurred in the Racine and Boston samples, respectively. The Boston sample (Table 8) from June 23, 1981 had the lowest volatile fraction. The Lansing sample (Table 10) also had a low volatile fraction, 16 percent.

The suspended solids concentration in the Boston and Racine samples varied from 149 mg/1 to 1,110 mg/1, while the Lansing sample was 159,900 mg/1. The volatile fraction of the suspended solids varied from 10 percent to 82 percent, but five of the seven samples were below 15 percent.

TABLE 4. CHARACTERISTICS OF STORMWATER RESIDUALS FROM RACINE, WISCONSIN, RETENTION POND. RUNOFF EVENT OCCURRED ON JUNE 28, 1980.

Parameter	Units	Total	Soluble
Total solids	mg/l	233	
Volatile total solids	mg/l	155	
Suspended solids	mg/l	149	
Volatile suspended solids	mg/l	122	
BOD_5	mg/l	11	
Total organic carbon	mg/l	29	
Total phosphorous (as P)	mg/l (mg/kg dry)	0.42 (<2,820)	<0.02
Total Kjeldahl nitrogen (as N)	mg/l (mg/kg dry)	3.48 (<23,360)	<0.30
NH_3	mg/l	0.52	
NO_2+NO_3 (as N)	mg/l	0.70	
pH		8.1	
Total coliforms	no./100 ml	87,000	
Fecal coliforms	no./100 ml	2,200	
PCB	µg/l (µg/kg dry)	0.19 (<1,275)	
DDT	µg/l (µg/kg dry)	<0.003 (<20)	
DDD	µg/l (µg/kg dry)	<0.005 (<34)	
DDE	µg/l (µg/kg dry)	<0.008 (<54)	
Aldrin	µg/l (µg/kg dry)	<0.002 (<13)	
Endrin	µg/l (µg/kg dry)	<0.005 (<34)	
Lindane	µg/l (µg/kg dry)	<0.004 (<27)	
Methoxychlor	µg/l (µg/kg dry)	<0.01 (<67)	
Dieldrin	µg/l (µg/kg dry)	<0.005 (<34)	
Mercury	mg/l (mg/kg dry)	<0.0003 (<2)	<0.0003
Arsenic	mg/l (mg/kg dry)	<0.01 (<67)	<0.01
Lead*	mg/l (mg/kg dry)	0.25 (1,280)	0.06
Zinc*	mg/l (mg/kg dry)	0.14 (740)	0.03
Iron*	mg/l (mg/kg dry)	6.6 (43,080)	0.18
Copper*	mg/l (mg/kg dry)	0.105 (200)	0.075
Nickel*	mg/l (mg/kg dry)	0.12 (300)	0.075
Chromium*	mg/l (mg/kg dry)	0.025 (70)	0.015
Cadmium*	mg/l (mg/kg dry)	0.01 (30)	0.005

*Analyses by Marquette University.

TABLE 5. CHARACTERISTICS OF STORMWATER RESIDUALS FROM RACINE WISCONSIN, RETENTION POND. RUNOFF EVENT OCCURRED ON SEPTEMBER 9, 1980.

Parameter	Units	Total	Soluble
Total solids	mg/l	793	
Volatile total solids	mg/l	104	
Suspended solids	mg/l	723	
Volatile suspended solids	mg/l	90	
BOD_5	mg/l	15	
Total organic carbon	mg/l (mg/kg dry)	23 (5,530)	19
Total phosphorous (as P)	mg/l	0.68	
Total Kjeldahl nitrogen (as N)	mg/l	3.5	
NO_2+NO_3	mg/l	0.41	
pH		7.5	
Total coliform	no./100 ml	74,000	
Fecal coliform	no./100 ml	71,000	
PCB	µg/l (µg/kg dry)	0.32 (290)	0.11
DDT	µg/l (µg/kg dry)	<0.004 (<6)	<0.004
DDD	µg/l (µg/kg dry)	<0.008 (<11)	<0.008
DDE	µg/l (µg/kg dry)	<0.015 (<21)	<0.015
Aldrin	µg/l (µg/kg dry)	<0.002 (<3)	<0.002
Endrin	µg/l (µg/kg dry)	<0.005 (<7)	<0.005
Lindane	µg/l (µg/kg dry)	<0.004 (<6)	<0.004
Methoxychlor	µg/l (µg/kg dry)	<0.02 (<20)	<0.02
Dieldrin	µg/l (µg/kg dry)	<0.005 (<7)	<0.005
Mercury	mg/l (mg/kg dry)	<0.0003 (<0.4)	<0.0003
Arsenic	mg/l (mg/kg dry)	<0.01 (<13)	<0.01
Lead*	mg/l (mg/kg dry)	0.85 (70)	0.80 [a]
Zinc*	mg/l (mg/kg dry)	0.33 (350)	0.08
Iron*	mg/l (mg/kg dry)	34.20 (42,050)	3.80
Copper*	mg/l (mg/kg dry)	0.10 (30)	0.08
Nickel*	mg/l (mg/kg dry)	0.14 (100)	0.07
Chromium*	mg/l (mg/kg dry)	0.10 (40)	0.07
Cadmium*	mg/l (mg/kg dry)	<0.01 (<14)	<0.01

*Analyses by Marquette University

[a] Samples were fixed with nitric acid prior to filtration. Soluble levels are thus inflated.

TABLE 6. CHARACTERISTICS OF STORMWATER RESIDUALS FROM SWIRL SOLIDS SEPARATOR IN BOSTON, MASSACHUSETTS. RUNOFF EVENT OCCURRED ON OCTOBER 25, 1980.

Parameter	Units	Total	Soluble
Total solids	mg/l	344	
Volatile total solids	mg/l	107	
Suspended solids	mg/l	235	
Volatile suspended solids	mg/l	30	
BOD_5	mg/l	24	
COD	mg/l (mg/kg dry)	130 (459,600)	22
Total organic carbon	mg/l (mg/kg dry)	39 (110,640)	13
Total phosphorous (as P)	mg/l (mg/kg dry)	0.46 (1,790)	0.04
Total Kjeldahl nitrogen (as N)	mg/l (mg/kg dry)	1.62 (<6,890)	<0.30
NH_3 (as N)	mg/l	<0.05	
NO_2+NO_3 (as N)	mg/l	0.10	
Oil and grease	mg/l	4	
pH		5.2	
Fecal coliform	no./100 ml	65,500	
Fecal streptococci	no./100 ml	16,725	
PCB	µg/l (µg/kg dry)	<0.01 (40)	
Mercury	mg/l (mg/kg dry)	0.0022 (8)	0.0004
Arsenic	mg/l (mg/kg dry)	<0.01 (<40)	<0.01
Lead*	mg/l (mg/kg dry)	0.4 (1110)	0.14
Zinc*	mg/l (mg/kg dry)	0.13 (380)	0.04
Iron*	mg/l (mg/kg dry)	7.67 (30,810)	0.43
Copper*	mg/l (mg/kg dry)	0.12 (260)	0.06
Nickel*	mg/l (mg/kg dry)	0.03 (40)	0.02
Chromium*	mg/l (mg/kg dry)	0.07 (40)	0.06
Cadmium*	mg/l (mg/kg dry)	<0.01 (<40)	<0.01

*Analyses by Marquette University

TABLE 7. CHARACTERISTICS OF STORMWATER RESIDUALS FROM HELICAL BEND SOLIDS SEPARATOR IN BOSTON, MASSACHUSETTS. RUNOFF EVENT OCCURRED ON OCTOBER 25, 1980.

Parameter	Units	Total	Soluble
Total solids	mg/l	366	
Volatile total solids	mg/l	158	
Suspended solids	mg/l	195	
Volatile suspended solids	mg/l	21	
BOD_5	mg/l	30	
COD	mg/l (mg/kg dry)	101 (338,460)	35
Total organic carbon	mg/l (mg/kg dry)	34 (82,050)	18
Total phosphorous (as P)	mg/l (mg/kg dry)	0.54 (1,740)	0.13
Total Kjeldahl nitrogen (as N)	mg/l (mg/kg dry)	2.05 (5,320)	0.8
NH_3 (as N)	mg/l	0.23	
NO_2+NO_3 (as N)	mg/l	0.07	
Oil and grease	mg/l	2	
pH		5.1	
Fecal coliform	no./100 ml	36,670	
Fecal streptococci	no./100 ml	9,000	
PCB	µg/l (µg/kg dry)	<0.01 (<50)	
Mercury	mg/l (mg/kg dry)	0.001(1)	0.0008
Arsenic	mg/l (mg/kg dry)	<0.01 (<50)	<0.01
Lead*	mg/l (mg/kg dry)	0.33 (870)	0.16
Zinc*	mg/l (mg/kg dry)	0.14 (560)	0.03
Iron*	mg/l (mg/kg dry)	6.13 (29,900)	0.30
Copper*	mg/l (mg/kg dry)	0.14 (310)	0.08
Nickel*	mg/l (mg/kg dry)	0.07 (50)	0.06
Chromium*	mg/l (mg/kg dry)	0.08 (100)	0.06
Cadmium*	mg/l (mg/kg dry)	<0.01 (<50)	<0.01)

*Analyses by Marquette University

TABLE 8. CHARACTERISTICS OF STORMWATER RESIDUAL FROM SWIRL SOLIDS SEPARATOR IN BOSTON, MASSACHUSETTS. RUNOFF EVENT OCCURRED ON JUNE 23, 1981.

Parameter	Units	Total	Soluble
Total solids	mg/l	1,140	
Volatile total solids	mg/l	125	
Suspended solids	mg/l	1,110	
Volatile suspended solids	mg/l	149	
BOD_5	mg/l (mg/kg dry)	27 (18,000)	7
COD	mg/l (mg/kg dry)	196 (153,000)	26
Total Organic Carbon	mg/l (mg/kg dry)	76 (54,000)	16
Total Phosphorous (as P)	mg/l (mg/kg dry)	1.32 (1,200)	0.02
Total Kjeldahl Nitrogen (as N)	mg/l (mg/kg dry)	3.5 (1,600)	1.7
NH_3 (as N)	mg/l	<0.1	<0.1
NO_2 and NO_3 (as N)	mg/l (mg/kg dry)	0.41 (<370)	<0.02
Oil and grease	mg/l	16	-
pH		6.0	
PCB	µg/l (µg/kg dry)	0.76 (470)	0.24
DDT	µg/l	<0.010	<0.010
DDD	µg/l	<0.008	<0.008
DDE	µg/l	<0.004	<0.004
Aldrin	µg/l	<0.005	<0.005
Endrin	µg/l	<0.005	<0.005
Lindane	µg/l	<0.003	<0.003
Methoxychlor	µg/l	<0.01	<0.01
Dieldrin	µg/l (µg/kg dry)	0.037 (14)	0.022
Mercury	mg/l	<0.0003	<0.0003
Arsenic	mg/l	<0.005	<0.005
Lead*	mg/l (mg/kg dry)	0.38 (310)	0.04
Zinc*	mg/l (mg/kg dry)	0.20 (80)	0.11
Iron*	mg/l (mg/kg dry)	30.8 (27,000)	0.49
Copper*	mg/l (mg/kg dry)	0.15 (18)	0.13
Nickel*	mg/l (mg/kg dry)	0.15 (90)	0.05
Chromium*	mg/l (mg/kg dry)	0.19 (150)	0.02
Cadmium*	mg/l	<0.01	<0.01

* Analyses by Marquette University

TABLE 9. CHARACTERISTICS OF STORMWATER RESIDUAL FROM HELICAL BEND SOLIDS SEPARATOR IN BOSTON, MASSACHUSETTS. RUNOFF EVENT OCCURRED ON JUNE 23, 1981.

Parameter	Units		Total	Soluble
Total solids	mg/l		950	
Volatile total solids	mg/l		310	
Suspended solids	mg/l		910	
Volatile suspended solids	mg/l		301	
BOD_5	mg/l	(mg/kg dry)	88 (85,000)	11
COD	mg/l	(mg/kg dry)	294 (281,000)	38
Total organic carbon	mg/l	(mg/kg dry)	84 (70,000)	20
Total Phosphorous (as P)	mg/l	(mg/kg dry)	1.32 (1,300)	0.12
Total Kieldahl Nitrogen (as N)	mg/l	(mg/kg dry)	5.0 (4,500)	0.9
NH_3 (as N)	mg/l		<0.1	<0.1
NO_2 and NO_3 (as N)	mg/l		<0.02	<0.02
Oil and grease	mg/l		79	
pH	-		5.8	
PCB	µg/l	(µg/kg dry)	1.12 (1,000)	0.20
DDT	µg/l		<0.010	<0.010
DDD	µg/l		<0.008	<0.008
DDE	µg/l		<0.004	<0.004
Aldrin	µg/l		<0.005	<0.005
Endrin	µg/l		<0.005	<0.005
Lindane	µg/l		<0.003	<0.003
Methoxychlor	µg/l		<0.01	<0.01
Dieldrin	µg/l	(µg/kg dry)	0.061 (25)	0.038
Mercury	mg/l		<0.0003	<0.0003
Arsenic	mg/l	(mg/kg dry)	0.012 (75)	<0.005
Lead*	mg/l	(mg/kg dry)	0.55 (550)	0.05
Zinc*	mg/l	(mg/kg dry)	0.25 (45)	0.21
Iron*	mg/l	(mg/kg dry)	29.2 (32,000)	0.45
Copper*	mg/l	(mg/kg dry)	0.05 (10)	0.04
Nickel*	mg/l	(mg/kg dry)	0.08 (45)	0.04
Chromium*	mg/l		0.12 (120)	0.01
Cadmium*			<0.01	<0.01

* Analyses by Marquette University

TABLE 10. CHARACTERISTICS OF STORMWATER RESIDUALS FROM UPSIZED STORM SEWER IN LANSING, MICHIGAN. RESIDUALS ACCUMULATED FROM RUNOFF EVENTS OCCURRING OVER A SIX MONTH PERIOD. SAMPLE COLLECTED ON NOVEMBER 13, 1980.

Parameter	Units	Total	Soluble
Total solids[1]	mg/l (mg/kg wet)	160,865** (152,200)	
Volatile total solids	mg/l (mg/kg wet)	25,800** (24,400)	
Suspended solids[2]	mg/l	159,900	
Volatile suspended solids	mg/l	24,600	
Dissolved solids	mg/l	965	
BOD_5	mg/l	4,260	
COD	mg/l (mg/kg dry)	44,300 (276,600)	67
Total organic carbon	mg/l (mg/kg dry)	15,500 (96,756)	30
Total phosphorous (as P)	mg/l (mg/kg dry)	135 (840)	
Total Kjeldahl nitrogen (as N)	mg/l (mg/kg dry)	2,250 (13,990)	
NH_3(as N)	mg/l	170	
NO_2+NO_3(as N)	mg/l	0.3	
Oil and grease	mg/l	1,185	
PCB	µg/l (µg/kg dry)	24.6 (150)	<0.33
DDT	µg/l (µg/kg dry)	2.5 (<15)	<0.07
DDD	µg/l (µg/kg dry)	13.8 (<90)	<0.03
DDE	µg/l (µg/kg dry)	<0.8 (<5)	<0.02
Aldrin	µg/l (µg/kg dry)	<1.2 (<10)	<0.03
Endrin	µg/l (µg/kg dry)	<1.4 (<10)	<0.03
Lindane	µg/l (µg/kg dry)	<0.8 (<5)	<0.02
Methoxychlor	µg/l (µg/kg dry)	<3.3 (<20)	<0.09
Dieldrin	µg/l (µg/kg dry)	<1.3 (<10)	<0.03
Mercury	mg/l (mg/kg dry)	0.005 (0.03)	0.003
Arsenic	mg/l	0.09	0.09
Lead*	mg/l (mg/kg dry)	64.6 (400)	0.5
Zinc*	mg/l (mg/kg dry)	37.6 (230)	0.04
Iron*	mg/l (mg/kg dry)	2970 (18,540)	5.5
Copper*	mg/l (mg/kg dry)	20.1 (125)	0.36
Nickel*	mg/l (mg/kg dry)	5.9 (40)	0.18
Chromium*	mg/l (mg/kg dry)	8.47 (50)	0.12
Cadmium*	mg/l (mg/kg dry)	0.95 (6)	0.04

[1]mg/l value obtained by addition of suspended and dissolved solids (mg/kg wet) value obtained by analysis

[2]Volumetric analysis

*Analyses by Marquette University

**Values by calculation

It should be noted that the relatively high percentage volatile solids observed (namely 67 percent volatile total solids and 82 percent volatile suspended solids) were the exception rather than the rule for the treated stormwater residuals investigated, and this exception warrants an explanation. The high volatile values observed were associated with the residuals obtained from the storage-sedimentation of the runoff event which occurred at the Racine site on June 28, 1980. The residuals data for that event are presented in Table 4. For that runoff event, the first flush, containing the majority of inert material, was missed. Therefore, the settled residuals from that runoff event were predominantly those from the extended runoff flow following the first flush. As may be seen from Table 4, the suspended solids of the settled residuals were predominantly volatile (organic).

In Figure 10, an illustration of the relative levels of solids concentrations in all of the samples collected is presented, as well as the levels of nutrients and oxygen demanding substances. Figure 10 shows clearly the significant difference in characteristics between the residuals collected from a single storm event and the residuals accumulated from multistorm events. The concentration of the oxygen demanding substances, organics, phosphorous, and nitrogen compounds from the Racine and Boston sites were all well below the level found in the residuals from the Lansing site. The storage of the residuals in the storm sewer sump and the continuous input of residuals into the system combined to produce a highly concentrated source of stormwater runoff residuals in the upsized pipe.

Figure 11 shows the relative concentration levels of the nine metals monitored in the stormwater residuals collected. The three most abundant metals in all samples were iron (18,540 mg/kg to 43,080 mg/kg), lead (70 mg/kg to 1,280 mg/kg), and zinc (45 mg/kg to 740 mg/kg). The next most abundant metals were copper (10 mg/kg to 310 mg/kg) and nickel (40 mg/kg to 300 mg/kg) followed by chromium (40 mg/kg to 150 mg/kg) and cadmium (0 to 30 mg/kg). Mercury and arsenic were present in extremely low quantities, and in some cases were not detectable.

An interesting point to be made here is the Lansing sample which, in all but two cases, had one of the lowest mass concentrations (mg/kg dry suspended) of a given metal (see Figure 11). Apparently the metal component of suspended solids in the Lansing runoff is lower than the metal component in the runoff from the Boston or Racine area.

The concentrations of chlorinated hydrocarbons (pesticides) in the residuals samples for Racine and Boston were very low. In fact, the pesticides level was below the detectable limit in all cases except one. For the Racine samples, the pesticide concentrations were all less than 20 nanograms per liter and in the June 23, 1981 Boston sample all the pesticides concentrations were less than 10 nanograms per liter except Dieldrin. Dieldrin was found at 37 nanograms per liter and 60 nanograms per liter in the swirl and helical bend samples, respectively. This level is relatively high and

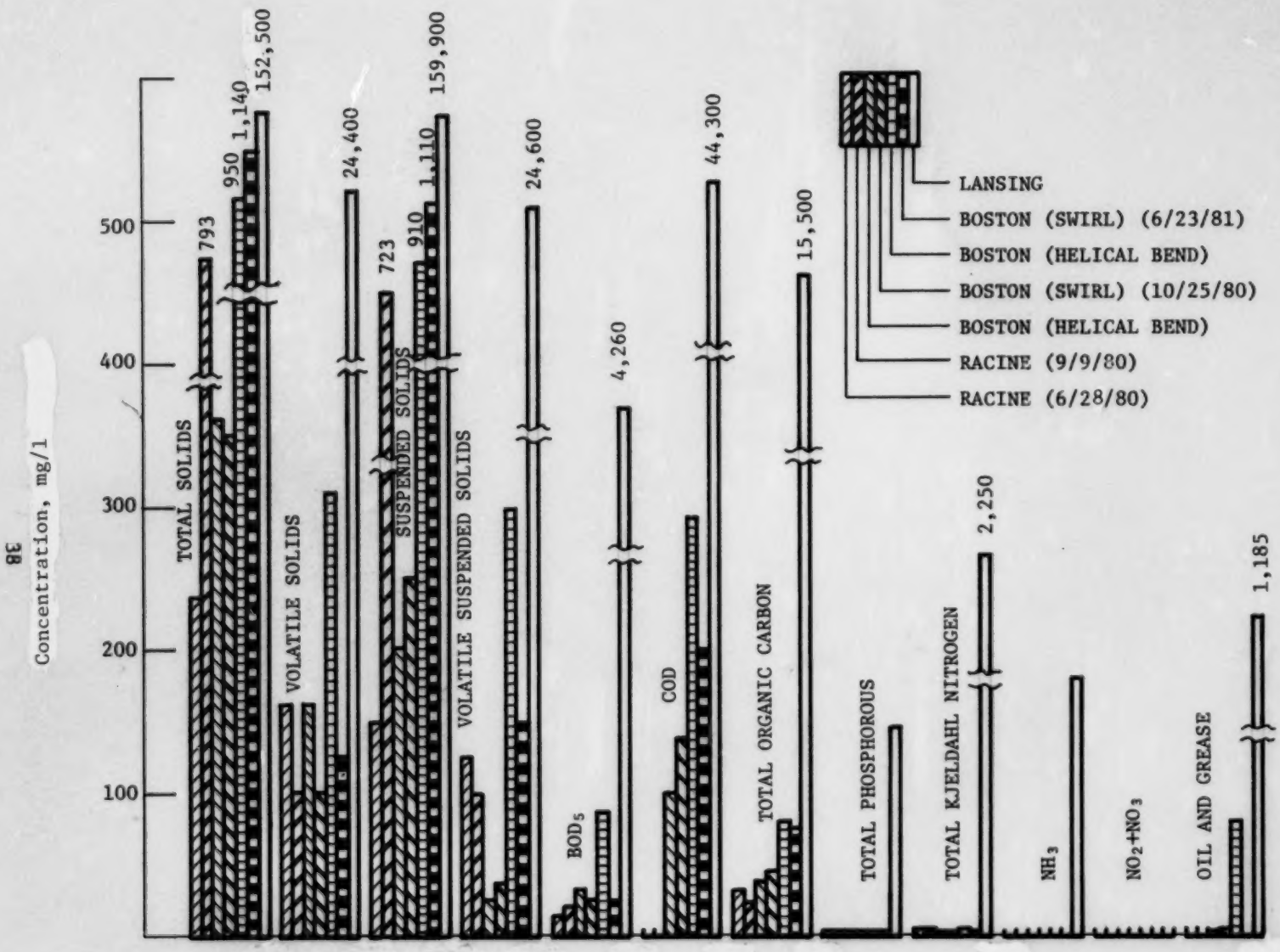


Figure 10. Bar chart showing relative concentrations of 12 parameters monitored in stormwater residuals.

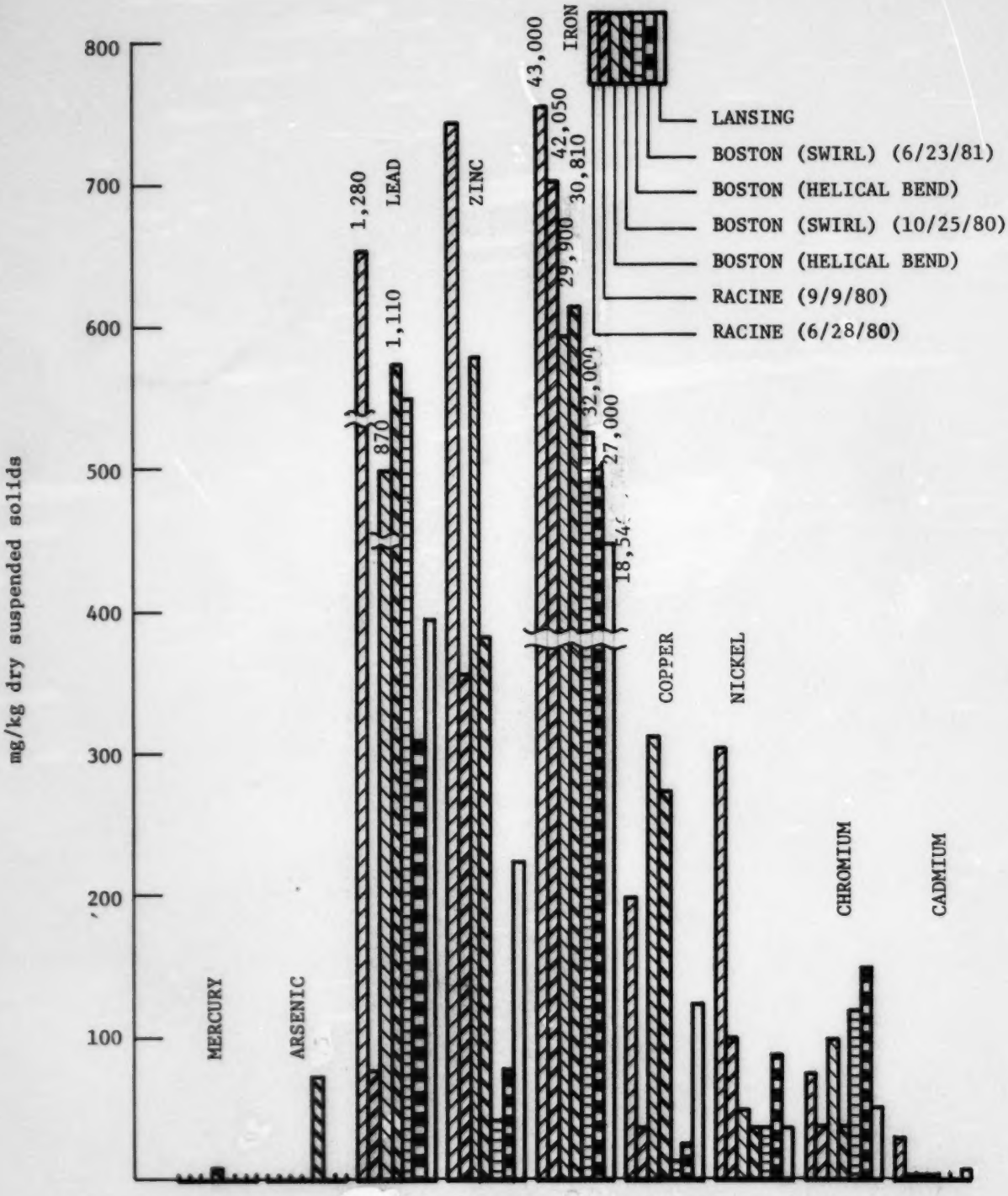


Figure 11. Bar chart showing relative mass concentrations of nine metals monitored in stormwater residuals.

is greater than the water quality criterion of 1.9 nanograms/liter for freshwater aquatic life (24 hour average concentration) (22). Also, the soluble concentration of Dieldrin (22 nanogram per liter from the swirl and 38 nanograms per liter from the helical bend) exceeds the water quality criterion. The Dieldrin in this runoff would probably not be deleterious to freshwater aquatic life if the receiving water had sufficient capacity to dilute the runoff, however, if the receiving waters were small in comparison there could be an adverse impact associated with the high Dieldrin concentration.

The concentration of PCB's in the Racine samples were 0.19 µg/1 and 0.32 µg/1 for the June and September events, respectively. These PCB levels were less than the 0.76 µg/1 and 1.12 µg/1 found in the swirl and helical bend samples for June 23, 1981. However, on a mass basis the Racine samples were 1,275 µg/kg dry suspended solids and 1,000 µg/kg dry suspended solids. The PCB levels in the swirl and helical bend samples from the October 25, 1980 event were below the detectable limit.

The maximum concentration of pesticides in the Lansing sample was between 0.8 µg/1 and 13.8 µg/1 which is between one to three orders of magnitude greater than the concentration found in Racine and Boston samples. It should be noted that the DDD and DDT concentrations were quite high in the Lansing sample, 13.8 µg/1 and 2.5 µg/1, respectively. A possible explanation for DDD being present in a higher concentration than DDT is that DDD is a common derivative of DDT found in anaerobic environments. Apparently, much of the DDT entering the sewer was converted to DDD over the six month storage period. The mass concentrations of pesticides in the Lansing sample were, however, comparable to the concentrations found in the Racine samples, 5 µg/kg to 90 µg/kg. The quantity of pesticides associated with the suspended solids appears then to be similar in both the Racine and Lansing samples.

The concentrations of PCB's in the Lansing sample (24.6 µg/1) was over 20 times greater than the concentration in the Racine samples. The mass concentration (150 µg/kg) is, however, lower than both Racine and the later Boston samples. The concentrations of PCB's in the October 25, 1980 Boston samples were the lowest of all samples in terms of µg/1 (<0.01 µg/1 for both samples) and in terms of µg/kg (<40 µg/kg from the swirl unit and <50 µg/kg from the helical bend unit). Organochloride pesticide analyses for the Boston site separator residue samples obtained during the October 25, 1980 storm event were not performed because of the possible abnormal effect on those analyses that might be caused by the peak foliage season in the Boston area which occurred just prior to the October 25, 1980 storm event. Large quantities of leaves were found in catch basins in the drainage area, resulting in the effective filtration of significant amounts of settleable material. This occurrence may also have contributed to the low PCB levels observed in these particular Boston site samples.

Characterization of the urban runoff residuals sampled here has shown the concentrations of various pollutants (solids, oxygen demanding substances, nutrients, pesticides, and heavy metals) that may be encountered from single runoff events (Racine and Boston) as well as from a multi-storm treatment system. The treatability of these stormwater residuals will be presented in the following section.

SECTION 6

BENCH SCALE TREATABILITY STUDIES

RACINE, WISCONSIN

For both runoff events in Racine (June and September of 1980), the stormwater was allowed to flow through a jury-rigged, field-assembled sedimentation basin. The basin was not necessarily designed to function as an efficient flow-through settling basin. Its purpose was to retain a representative portion of the stormwater flow, permit the solids in the retained volume to settle under relatively quiescent conditions and to obtain samples of the accumulated settled sludge residue. The data obtained from the September 9, 1980 storm event showed that the field basin was not an efficient flow-through device (56 mg/1 influent syspended solids; 58 mg/1 effluent suspended solids). However, the basin functioned satisfactorily for its intended purpose of providing settled sludge residuals from stormwater events for treatability studies.

The volume of settleable solids in the stormwater residuals from the June and September event were 2 and 6 ml/liter*. The June event had seven antecedent dry days while the September event had three antecedent dry days. Normally, one would expect settleable solids to increase with the number of antecedent dry days. On the other hand, it may be remembered that for the June 1980 storm event, much of the first flush was missed, which would result in a smaller settleable sludge volume. In any event, the net result was that the volume of stormwater runoff retained for settling on September 9, 1980 was 2.25 times greater than that retained on June 28, 1980. As a result, a larger quantity of settleable solids was obtained in the settled fraction of the stormwater runoff event on September 9, 1980.

Figure 12 presents a schematic diagram of the treatability tests conducted on the Racine sludge samples. Tables 11 to 13 show the results of bench scale thickening and centrifugation tests for the Racine samples as well as the other two sites. Test results showed that the residuals could be gravity thickened from 233 mg/1 to 100,000 mg/1 total solids for the June sample and from 793 mg/1 to 90,000 mg/1 for the September sample. The supernatant suspended solids for the two Racine samples were 41 mg/1 and 43 mg/1. This represents a 72 percent reduction in suspended solids for the June event and 94 percent reduction for the September event (Table 12). The average particle settling velocity was twice as high in the September event than the June event; increasing from 4 to 8 cm/min.

* 1.0 ml/liter = 1.0 liter/m^3

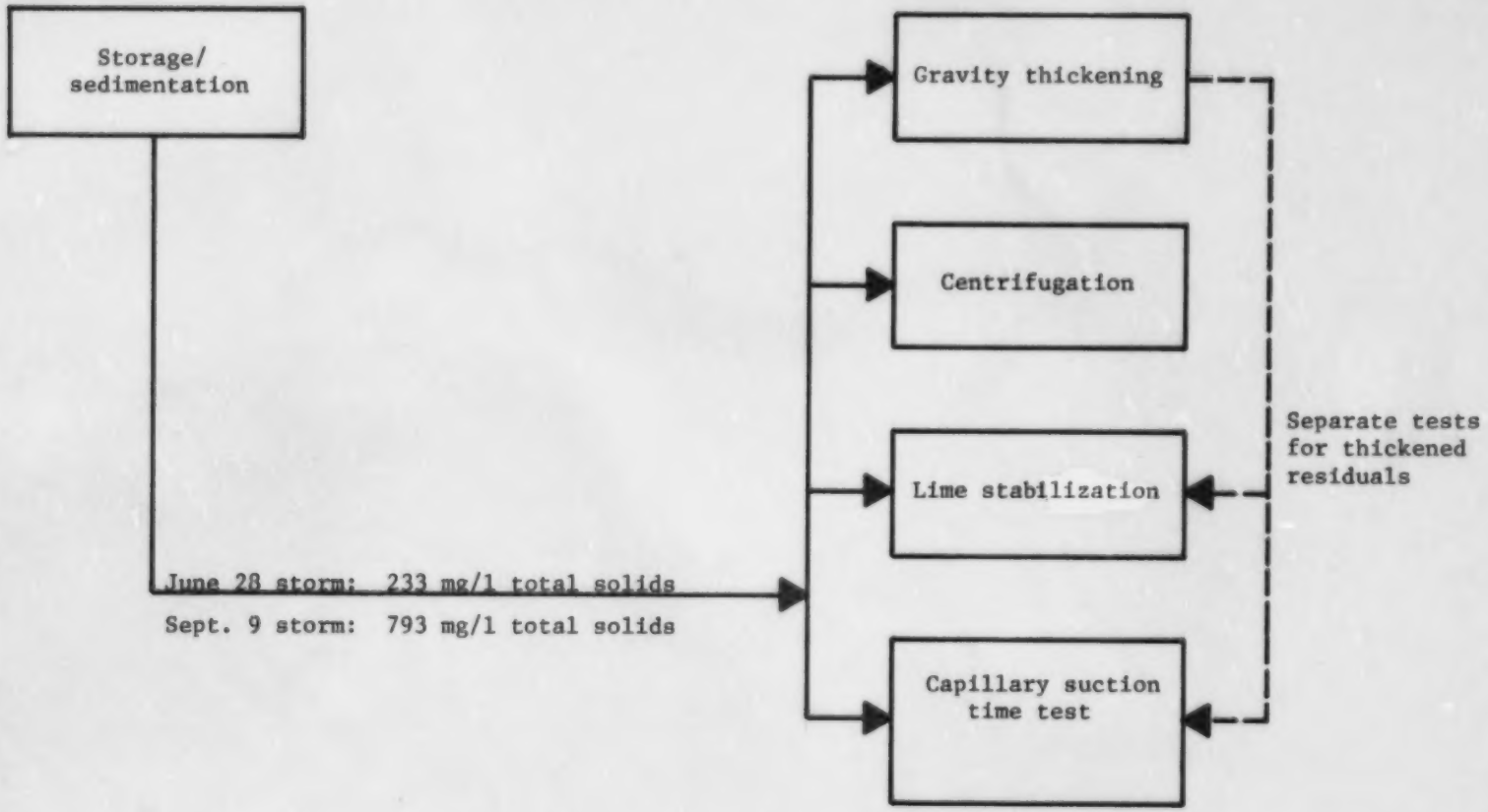


Figure 12. Racine, WI. Bench scale treatability tests.

TABLE 11. RESULTS OF BENCH SCALE GRAVITY THICKENING TESTS ON STORMWATER RUNOFF RESIDUALS FROM RACINE, WI; LANSING, MI; AND BOSTON, MA

	Racine, WI		Lansing, MI	Boston, MA 10/25/80		Boston, MA 6/23/81	
	June 28, 1980	Sept. 9, 1980		Swirl	Helical Bend	Swirl	Helical Bend
Settleable solids, ml/liter	2	6	590	0.6	0.3	3.5	2.2
Raw suspended solids, mg/l	149	723	159,900	235	195	1140	950
Thickened residuals							
Total solids, mg/l	100,000	90,000	367,000	139,000	190,000	151,000	151,000
Vol. total solids, mg/l	15,000	-	37,500	111,000	156,000	120,000	119,000
Supernatant							
Volume, ml/l	998	994	410	999.4	999.7	996.5	997.8
Suspended solids, mg/l	41	43	400	93	106	302	179
Vol. suspended solids, mg/l	20	9	120	14	19	42	47
Average particle settling velocity, cm/min.	4	8	0.15*	8	8	13	17

* Zone settling occurred with this sample.

TABLE 12. SOLIDS RECOVERY DATA FROM CENTRIFUGATION AND GRAVITY THICKENING TESTS ON URBAN STORMWATER RUNOFF RESIDUALS

Site	Centrifugation							Gravity Thickening				
	Feed suspended, mg/l	Spin time, seconds	Centrifugal force, g	Centrate Volume ml	Centrate Volume Vol%	Centrate Solids mg/l	Solids recovery, %	Feed Solids, mg/l	Supernatant Volume ml	Supernatant Volume Vol%	Supernatant Solids mg/l	Solids recovery, %
Racine, WI (6/28/80)	149	30	400	158	99	16	89.3	149	998	99.80	41	72.5
	149	30	800	158	99	12	91.9					
	149	90	400	158	99	6	95.8					
	149	90	800	158	99	8	94.6					
(9/9/80)	723	30	400	158	99	25	96.5	723	994	99.40	43	94.0
	723	30	800	158	99	18	97.5					
	723	90	400	158	99	15	97.9					
	723	90	800	158	99	10	98.6					
Boston, MA (Swirl) (10/25/80)	235	30	400	>159	99+	42	82.1	235	999.4	99.94	93	60.4
	235	30	800	>159	99+	37	84.3					
	235	90	400	>159	99+	31	86.8					
	235	90	800	>159	99+	19	91.9					
(Helical Bend)	195	30	400	>159	99+	31	84.1	195	999.7	99.97	106	45.6
	195	30	800	>159	99+	35	82.1					
	195	90	400	>159	99+	44	77.4					
	195	90	800	>159	99+	24	87.7					
(6/23/81 Swirl)	1140	30	400	>159	99+	172	84.9	1140	996.5	99.65	302	73.5
	1140	30	800	>159	99+	149	86.9					
	1140	90	400	>159	99+	130	88.6					
	1140	90	800	>159	99+	87	92.4					
(Helical Bend)	950	30	400	>159	99+	40	95.6	950	997.8	99.78	179	81.1
	950	30	800	>159	99+	48	94.9					
	950	90	400	>159	99+	38	96.0					
	950	90	800	>159	99+	26	96.9					
Lansing, MI	159,900	30	400	108	67.7	22,430	86.0	159,000	410	41.00	400	99.7
	159,900	30	800	108	67.7	12,375	92.3					
	159,900	90	400	103	64.4	856	99.5					
	159,900	90	800	110	69.0	812	99.5					

TABLE 13. RESULTS OF BATCH CENTRIFUGATION TESTS ON STORMWATER RUNOFF RESIDUALS FROM RACINE, WI; LANSING, MI; AND BOSTON, MA

Centrifugal force g's	Spin time seconds		Racine, WI		Lansing, MI	Boston, MA 10/25/81		Boston, MA 6/23/81	
			June 28, 1980	Sept. 9, 1980		Swirl	Helical Bend	Swirl	Helical Bend
400	30	Centrate, mg/l							
		Suspended solids	16	25	22,400	42	31	172	40
		Vol. suspended solids	15	7	5,900	18	23	20	12
		Cake, mg/l							
		Total solids	120,000	140,000	547,700	100,000*	100,000*	130,000*	100,000*
		Vol. total solids	18,000	-	50,300	80,000	80,000	85,000	75,000
		Cake volume, ml/160 ml	<2	2	58	<1	<1	<1	<1
400	90	Centrate, mg/l							
		Suspended solids	12	15	860	31	44	130	38
		Vol. total solids	11	4	320	16	16	13	17
		Cake, mg/l							
		Total solids	120,000	130,000	504,900	100,000*	100,000*	130,000*	100,000*
		Vol. total solids	16,000	-	58,100	80,000	80,000	85,000	80,000
		Cake volume, ml/160 ml	<2	2	65	<1	<1	1	<1
800	30	Centrate, mg/l							
		Suspended solids	6	18	12,400	37	35	149	48
		Vol. total solids	5	5	3,300	25	29	23	10
		Cake, mg/l							
		Total solids	120,000	140,000	547,000	100,000*	100,000*	130,000*	100,000*
		Vol. total solids	19,000	-	47,500	80,000	80,000	85,000	75,000
		Cake volume, ml/160 ml	<2	2	61	<1	<1	1	<1
800	90	Centrate, mg/l							
		Suspended solids	8	10	810	19	24	87	26
		Vol. suspended solids	6	4	350	6	13	12	10
		Cake, mg/l							
		Total solids	130,000	120,000	491,300	100,000*	100,000*	130,000*	100,000*
		Vol. total solids	20,000	-	65,900	80,000	80,000	85,000	80,000
		Cake volume, ml/160 ml	<2	2	54	<1	<1	1	1

* Only very small quantities of thickened residuals could be obtained, these concentrations are estimates.

Table 14 presents data showing how sedimentation reduces the concentration of parameters that are associated with suspended solids in an unthickened sample. The calculations in the table assume that the parameters measured are uniformly associated with the suspended solids present in the sample. Many of the pesticides and two of the metals were consistently measured at undetectable levels, so the concentration is presented as a maximum value before and after sedimentation.

The results of the centrifugation tests show that only a small variation in sludge cake total solids could be expected over the range of variables tested. For the June tests the total solids was 12 percent in three of the tests and 13 percent in only one. Table 13 presents the results of the Racine centrifuge sample along with the results from the other two sites. The most notable impact of centrifuge spin time and g force is on the centrate suspended solids. The suspended solids for the June sample decreased from 16 mg/1 at a spin time of 30 seconds and 400 g force to 6 mg/1 at the same spin time and twice the g force. For the September event the decrease was from 25 mg/1 to 10 mg/1 when going from a spin time of 30 seconds and g force of 400 to a spin time of 90 seconds. The cake solids concentration showed no apparent relationship to spin time and g force. The total solids of the centrifuged cake varied from 12 percent to 14 percent.

The centrifuge tests showed a suspended solids removal efficiency of between 89 percent and 96 percent for residuals from the June event and 97 percent to 99 percent for residuals from the September event (Table 12).

The lime stabilization test data presented in Table 15 show that the lime required for stabilizing runoff residuals (adding lime to raise pH to 12.5 for one-half hour; this ensures pH will stay above a pH of 12.0 for two hours) appears to increase with increasing solids. The soluble base buffering capacity of unthickened and thickened residuals are probably equivalent. The increase in lime required to stabilize thickened residuals would then be due to an increase in the concentration of base buffering capacity associated with settleable solids. For the June and September samples the concentration of lime required for stabilization increased from 1.2 and 1.3 grams CaO per liter for unthickened residuals to 6 and 4.3 grams CaO per liter for thickened residuals respectively. However, the quantity of lime based on volume treated is significantly less for the thickened residuals due to the separation of water and its associated lime demand.

Data presented in Table 16 are from capillary suction time (CST) tests. The CST test determines the relative dewaterability of sludges by measuring the rate of withdrawal of water from a sample by capillary forces. Residuals for the September runoff event showed a large decrease in the dewatering rate for thickened residuals as compared to unthickened residuals. The capillary suction time (CST) increased from 7 seconds to over 120 seconds. The thickened residuals in the June event had a much lower CST of 25 seconds. A high CST is expected for thickened sludges, however, the reason for the larger difference in CST for the thickened residuals from June and September is not readily apparent.

TABLE 14. CONCENTRATION OF SELECTED PARAMETERS IN MIXED RESIDUALS BEFORE THICKENING AND SUPERNATANT AFTER THICKENING*. SAMPLES WERE COLLECTED FROM STORMWATER RETENTION POND IN RACINE, WI ON JUNE 28, 1980 AND SEPTEMBER 9, 1980.

		June 28, 1980		September 9, 1980	
Parameter	Units	Before thickening	After thickening	Before thickening	After thickening
PCB	µg/l	0.19	0.07	0.32	0.12
DDD	µg/l	<0.005	<0.002	<0.004	<0.004
DDE	µg/l	<0.003	<0.001	<0.008	<0.008
DDT	µg/l	<0.008	<0.003	<0.015	<0.015
Aldrin	µg/l	<0.002	<0.001	<0.002	<0.002
Endrin	µg/l	<0.005	<0.002	<0.005	<0.005
Lindane	µg/l	<0.004	<0.002	<0.004	<0.004
Methoxychlor	µg/l	<0.01	<0.004	<0.02	<0.02
Dieldrin	µg/l	<0.005	<0.002	<0.005	<0.005
Mercury	mg/l	<0.0003	<0.0001	<0.0003	<0.0003
Arsenic	mg/l	<0.01	<0.004	<0.01	<0.01
Lead	mg/l	0.25	0.13	0.85	0.80
Zinc	mg/l	0.14	0.07	0.33	0.10
Iron	mg/l	6.6	2.62	34.20	5.93
Copper	mg/l	0.105	0.09	0.10	0.08
Nickel	mg/l	0.12	0.09	0.14	0.07
Chromium	mg/l	0.025	0.02	0.10	0.07
Cadmium	mg/l	0.01	0.007	<0.01	0.01

* Concentrations given here assume pollutants are uniformly distributed between settleable and non-settleable suspended solids. Laboratory thickening data was used to calculate pollutant reduction.

TABLE 15. RESULTS OF LIME STABILIZATION TESTS ON STORMWATER RUNOFF RESIDUALS FROM RACINE, WI; LANSING, MI; AND BOSTON, MA

		Racine, WI		Lansing, MI	Boston, MA 10/25/80		Boston, MA 6/23/81	
		June 28, 1980	Sept. 9, 1980		Swirl	Helical Bend	Swirl	Helical Bend
Unthickened residuals	CaO, g/liter	1.2	1.3	22.0	1.3	1.9	3.8	6.6
	Initial pH	8.1	7.2	7.0	7.0	8.0	7.1	5.9
	Final pH	12.4	12.4	12.3	12.5	12.5	12.4	12.4
Thickened residuals*	CaO, g/l	6	4.3	-	6.3	4.3	11.5	10.0
	Initial pH	7.7	7.2	-	8.2	7.2	5.6	5.8
	Final pH	12.4	12.4	-	12.5	12.5	12.5	12.3

* Residuals thickened by gravity.

TABLE 16. RESULTS OF CAPILLARY SUCTION TIME TEST ON STORMWATER RUNOFF RESIDUALS FROM RACINE, WI; LANSING, MI; AND BOSTON, MA[a]

		Racine, WI		Lansing, MI	Boston, MA 10/25/80		Boston, MA 6/23/81	
		June 28, 1980	Sept. 9, 1980		Swirl	Helical Bend	Swirl	Helical Bend
Unthickened residuals	Volume, ml	-	10	10	5	5	5	8
	CST[c], sec	-	7	155	10	10	15	10
	Feed Solids, %		0.07	15.99	0.02	0.02	0.11	0.10
Thickened residuals[b]	Volume, ml	9	10	-	6	6	5	8
	CST[c], sec	25	>120	-	55	90	40	33
	Feed Solids, %	10.0	9.0	-	13.9	19.0	15.1	15.1

a Capillary suction time test for each sample was conducted using 2 pads.
b Residuals thickened by gravity.
c Capillary suction time.

LANSING, MICHIGAN

Figure 13 presents the schematic diagram for the treatability tests conducted on the Lansing sample. The residuals collected from Lansing had accumulated for six months in the sump of an upsized storm sewer. However, Analysis of influent and effluent samples of stormwater runoff showed that some of the suspended solids were scoured from the up-sized conduit sump.

Table 11 presents the results of the gravity thickening tests. The concentration of the residuals collected from Lansing were significantly greater than those from Racine or Boston because the stormwater runoff residuals were allowed to settle for an extended period (several months). When the sample was taken from the sump, the residuals were quite compact. Thickening tests essentially involved resuspending the solids and recording the settling rate. Unlike the Racine and Boston samples the residuals were concentrated enough for zone settling to occur. The settling rate was calculated at 0.15 cm/min. This settling rate was for the interface, and does not represent individual grit-like particle settling rates. During the thickening test individual grit-like particles were observed settling out at a greater rate than the interface settling rate. These grit-like particles were similar to those that settled in the Racine and Boston samples.

The total solids concentration of the thickened residuals was 367,000 mg/l (37,500 mg/l volatile total solids) or 2.4 times the unthickened concentration. This value is actually the average concentration of the two regions (zone settling region and discrete particle settling region) described above. A second thickening test was conducted and it was found that the discrete particles thickened to a concentration of 360,000 mg/l total solids (37,000 mg/l volatile total solids) while the zone settling region thickened to 165,000 mg/l total solids (30,900 mg/l volatile total solids). Discrete particles settled to a volume of 210 ml/liter while the volume occupied by the solids in the zone settling region was 48 ml/liter.

The volume of settleable solids was measured at 590 ml/liter as shown in Table 11. Similarly, Table 11 shows the corresponding measured supernatant volume, 410 ml/liter. It should be restated here that the residuals that settled in the storm sewer were probably at the maximum concentration because they were allowed to thicken over the six month accumulation period.

The suspended solids concentration in the supernantant from the gravity thickening test was 400 mg/l (120 mg/l volatile suspended solids), Table 11. This represents a removal rate in excess of 99 percent. The high percentage of suspended solids settling out of the Lansing sample is probably attributed to the zone settling. The solids in the zone settling region just below the interface will trap or filter smaller solids out of the liquid phase. Thus, these solids which may have too

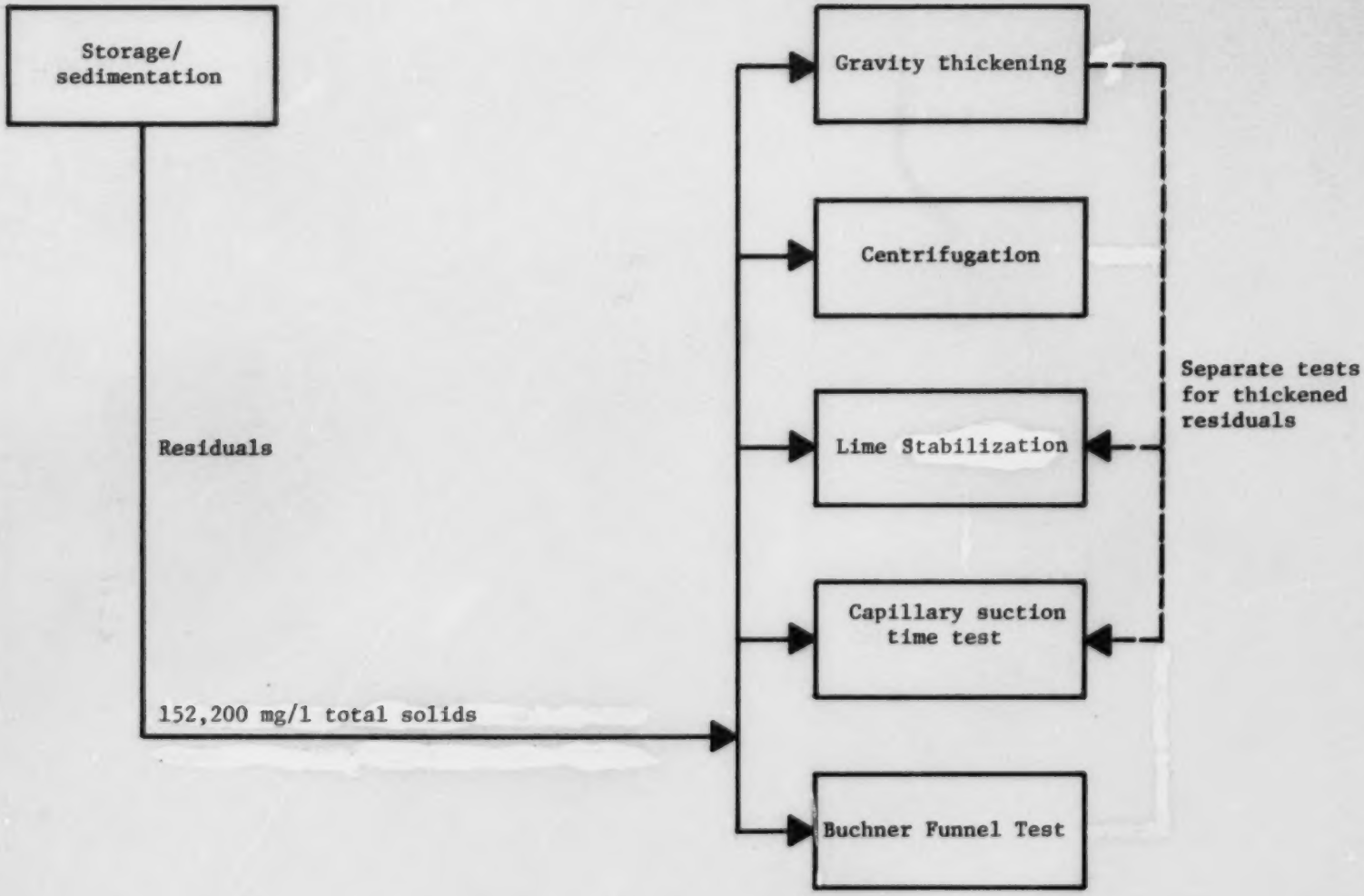


Figure 13. Lansing, MI. Bench scale treatability tests.

low a settling velocity to settle out as discrete particles are removed from the supernatant and the solids thickening efficiency is increased. Table 17 shows how sedimentation reduced the concentration of parameters associated with suspended solids in an unthickened sample. Of all the individual parameters listed in Table 17, only iron (Fe) and total Kjeldahl nitrogen (TKN) were found in significant concentrations in the supernatant at 14 mg/1 and 20 mg/1, respectively. From Table 17, the COD concentration in the supernatant was 200 mg/1. This represented one-half of the total suspended solids concentration in the supernatant, 400 mg/1, Table 11.

Results of the centrifugation tests show that spin time is critical to reducing suspended solids content of the centrate, that is, improving solids capture. For example, at a g force of 400, increasing the spin time from 30 to 90 seconds reduced the centrate suspended solids from 22,430 mg/1 to 856 mg/1. At a g force of 800, increasing the spin time from 30 to 90 seconds reduced the centrate suspended solids from 12,375 mg/1 to 812 mg/1. On the other hand, at an equivalent spin time of 30 seconds, increasing the g force from 400 to 800 reduced the centrate suspended solids from 22,430 mg/1 to 12,375 mg/1, while at a spin time of 90 seconds the same increase in g force reduced the centrate suspended from 856 mg/1 to 812 mg/1. Although centrifugation spin time had an appreciable effect on solids capture, an appreciable effect on cake solids content was not observed.

The lime stabilization test showed the unthickened Lansing residuals to have a greater soluble base buffering capacity than the thickened residuals from Racine. The concentration of total solids in the unthickened Lansing sample was 1.5 times greater than the thickened residuals collected in June from Racine and 1.7 times greater than the thickened residuals collected in September from Racine. The lime requirements for the unthickened Lansing sample was 22 g CaO/liter, which is 3.7 times the lime required to stabilize the thickened residuals collected in June from Racine and 5.1 times greater than the lime required to stabilize the thickened residuals collected in September from Racine. Apparently long term storage of stormwater runoff residuals may increase the lime required for residuals stabilization. The fact that the residuals came from different drainage basins must also be considered when analyzing the results of these tests.

No results were obtained on the lime required to stabilize thickened residuals from Lansing. Mixing the thickened sludge was somewhat like mixing a bucket of wet sand. Because a completely mixed sample could not be obtained no testing was initiated.

One capillary suction time (CST) test was performed on the Lansing sample transported from the test site. The results of the CST test performed on the unthickened raw sludge sample is presented in Table 16. Note that the feed solids concentration of the sample tested was 15.99 percent. From Table 16, comparison of the Lansing CST results with those of Boston

TABLE 17. CONCENTRATION OF SELECTED PARAMETERS IN MIXED RESIDUALS BEFORE THICKENING AND SUPERNATANT AFTER THICKENING* SAMPLE WAS COLLECTED FROM AN UPSIZED STORM SEWER IN LANSING, MI

Parameter	Units	Before thickening	After thickening
TOC	mg/1	15,500	76
COD	mg/1	44,300	200
Total phosphorous (P)	mg/1	135	0.8
TKN (N)	mg/1	2,250	20
PCB	µg/1	24.6	<0.40
DDD	µg/1	13.8	<0.07
DDE	µg/1	<0.8	<0.02
DDT	µg/1	<2.5	<0.08
Aldrin	µg/1	<1.2	<0.03
Endrin	µg/1	<1.4	<0.03
Lindane	µg/1	<0.8	<0.02
Methoxychlor	µg/1	<3.3	<0.09
Dieldrin	µg/1	<1.3	<0.03
Cd	mg/1	0.95	0.04
Cr	mg/1	8.47	0.15
Cu	mg/1	20.1	0.42
Fe	mg/1	2,970	14.00
Pb	mg/1	64.6	0.70
Ni	mg/1	5.89	0.20
Zn	mg/1	37.6	0.15
As	mg/1	0.09	0.09
Ag	mg/1	0.005	0.0003

* Concentrations given here assume pollutants are uniformly distributed between settleable and non-settleable suspended solids. Laboratory thickening data was used to calculate pollutant reduction.

(thickened residuals, September 9, 1980) indicates that the Lansing sludge is probably more amenable to further dewatering than the Racine sludge but less amenable to further dewatering (say, by filtration) than the Boston sludge.

The dewaterability of the gravity thickened residuals was determined by using a buchner funnel apparatus. No coagulants were added to the sample prior to filtration. The rate of dewatering was constant over the 7-minute filter time. The residuals were dewatered to 68.9 percent solids and the filtrate suspended solids were 94 mg/l (42 mg/l volatile suspended solids). The specific resistance of the filter cake was calculated to be 1.62×10^{16} m/kg (1.65×10^{12} sec^2/gm) which is slightly higher than the specific resistance of thickened waste activated sludge conditioned with ferric chloride.

BOSTON, MASSACHUSETTS

Figure 14 presents a schematic diagram showing the treatability tests conducted on the October 25, 1980 and June 23, 1981, stormwater runoff residuals samples from Boston. The swirl and helical bend samples from the October, 1980 event were each composited over a thrity minute period. Sampling from the helical bend unit was begun 77 minutes after the unit became operational, while sampling from the swirl unit started after it had been operating for 127 minutes. The swirl and helical bend samples from the June, 1981 event were each composited over a 65 minute period. Sampling from the swirl and helical bend units were begun 4 minutes after the units became operational. There was a seven day dry period before the October, 1980 event, and a two day dry period before the June, 1981 event.

The stormwater runoff residuals obtained from the swirl and helical bend units during the 1980 event had a suspended solids concentration of 235 mg/l and 195 mg/l, respectively. The residuals from the June, 1981 event were much higher - 1140 mg/l from the swirl unit and 950 mg/l from the helical bend. The higher suspended solids level in the June, 1981 runoff may be attributable to the fact that the composite samples included the initial runoff or "first flush". The samples from October, 1980 did not include portions from the first flush for reasons previously enumerated in Section 5 of this report. Briefly, in October 1980, just prior to performing the test run, the peak foliage occurred in the Boston area, resulting in large quantities of leaves covering the catch basins in the area, effectively filtering out significant amounts of settleable material associated with the first flush of the storm event.

The settleable solids in the October, 1980 samples were 0.6 ml/l and 0.3 ml/l for the swirl and helical bend, respectively. The concentration of the gravity thickened residuals (Table 11) from the swirl unit was 139,000 mg/l total solids (111,000 mg/l volatile total solids) and 190,000 mg/l total solids (156,000 mg/l volatile total solids) for the helical bend.

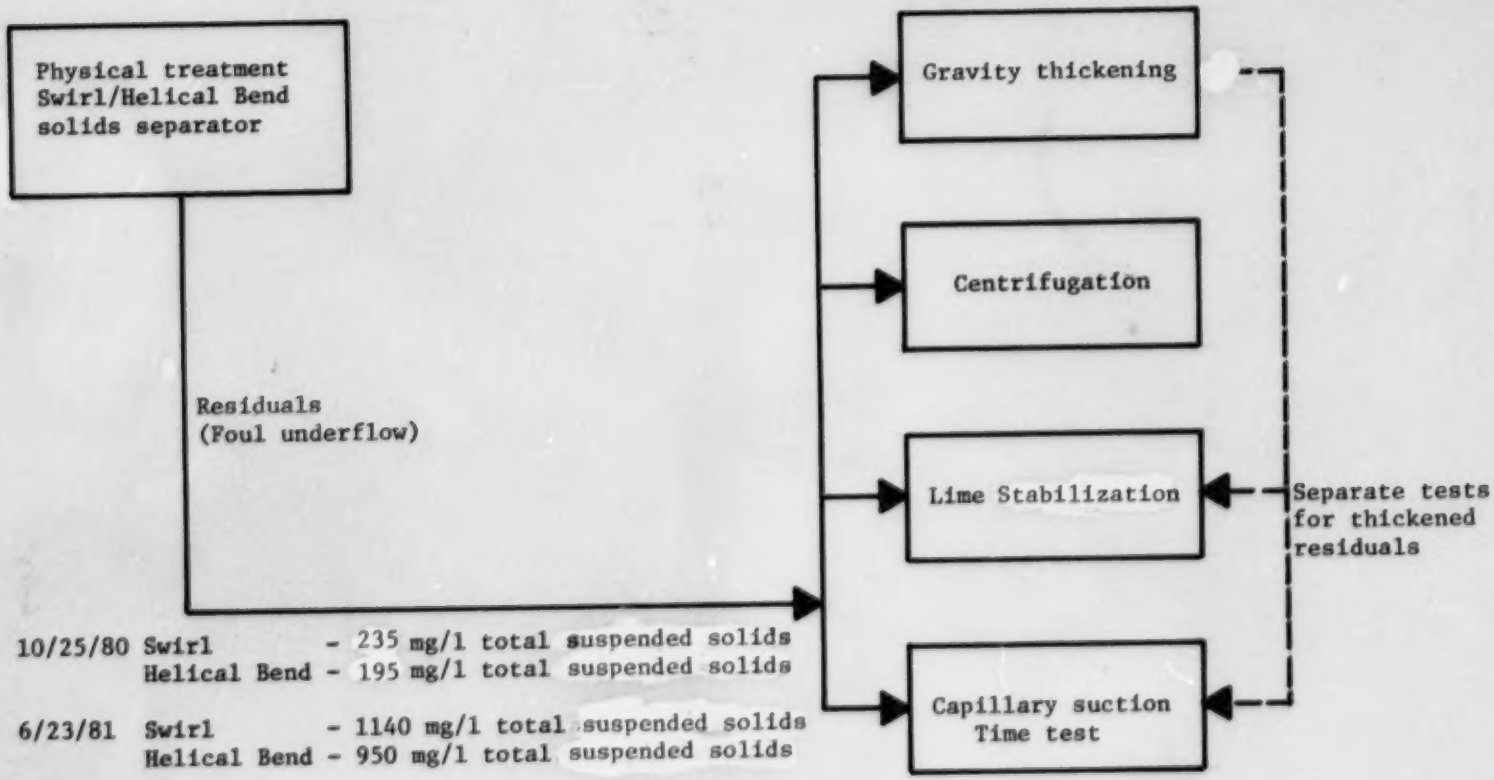


Figure 14. Boston, MA. Bench scale treatability tests.

The supernatant suspended solids from the October, 1980 swirl sample was 93 mg/1 (14 mg/1 volatile) while the helical bend supernatant had 106 mg/1 suspended solids (19 mg/1 volatile). Thus 60 percent of the suspended solids in the swirl unit were removed while only 46 percent of the suspended solids in the helical bend unit were captured. The June, 1981 samples had more settleable solids than the October samples. The gravity thickened samples had total solids concentrations about midway between the October swirl and helical bend samples. The June, 1981 sample from the swirl unit had 3.5 ml/1 setteable solids while the helical bend had 2.2 ml/1. The total solids concentration of the gravity thickened residuals was the same for both units - 151,000 mg/1, with the swirl unit having a slightly greater volatile fraction - 120,000 mg/1 versus 119,000 mg/1 for the helical bend. The supernantant suspended solids concentration was much higher in the gravity thickened swirl sample - 302 mg/1 (42 mg/1 volatile), than in the helical bend sample - 179 mg/1 (47 mg/1 volatile). Thus 74 percent of the suspended solids in the swirl sample were settleable while 81 percent of the suspended solids in this helical bend sample were settleable.

Overall the residuals produced from the swirl and helical bend units are readily thickened with good solids recovery. Based on the data one may expect that as the residuals solids concentration increases the volume of settleable solids will also increase.

The fraction of settleable suspended solids is an approximation of the level of pollutant removal that may be obtained with gravity thickening. The data on the characteristics of the residuals presented in the previous section shows the fraction of each pollutant associated with suspended solids. Table 18 presents the concentration of several pollutants before and after gravity thickening of swirl and helical bend residuals. The greatest level of pollutant reduction obviously occurs with those pollutants that have a high degree of association with suspended solids. The combination of solids recovery and the level of association between pollutants and suspended solids will thus determine what percent of the pollutants will be captured by gravity thickening.

Centrifugation of residuals from the swirl and helical bend units produced centrate suspended solids concentrations well below the level obtainable by gravity thickening (Table 12). Solids recovery varied from 77 percent to 92 percent in the October, 1980 samples and 85 percent to 97 percent in the June, 1981 samples. The lowest centrate suspended solids concentrations were obtained by centrifugation at the highest g force and longest spin time in each sample (90 seconds and 800 g's). Estimates of the centrifuge cake solids content suggest little variation in concentration for the spin time and g forces used here. The volume of the centrifuge cake was quite small in all cases (less than 0.1 ml from 160 ml of residuals) so accurate measurement of the cake solids was not feasible for either the swirl or helical bend samples.

TABLE 18. CONCENTRATION OF SELECTED PARAMETERS IN MIXED RESIDUALS BEFORE THICKENING AND SUPERNATANT AFTER THICKENING*. SAMPLES WERE COLLECTED FROM THE SWIRL AND HELICAL BEND SOLIDS SEPARATORS.

		October 25, 1980				June 23, 1981			
		Swirl		Helical Bend		Swirl		Helical Bend	
Parameter	Units	Before thickening	After thickening	Before thickening	After thickening	Before thickening	After thickening	Before thickening	After thickening
Total Organic Carbon	mg/l	39	23	34	24	76	32	84	32
Chemical Oxygen Demand	mg/l	130	65	101	61	196	71	294	86
Total Phosphorous	mg/l	0.46	0.21	0.54	0.29	1.32	0.36	1.32	0.35
TKN	mg/l	1.62	<0.95	2.05	1.3	3.5	2.2	5.0	1.67
PCB	µg/l	<0.10	<0.04	<0.10	<0.05	0.76	0.37	1.12	0.37
DDD	µg/l					<0.008	<0.002	<0.008	<0.002
DDE	µg/l					<0.004	<0.001	<0.004	<0.001
DDT	µg/l					<0.01	<0.003	<0.01	<0.002
Aldrin	µg/l					<0.005	<0.001	<0.005	<0.001
Endrin	µg/l					<0.005	<0.001	<0.005	<0.001
Lindane	µg/l					<0.003	<0.001	<0.003	<0.001
Methoxychlor	µg/l					<0.01	<0.003	<0.01	<0.002
Dieldrin	µg/l					0.037	0.026	0.061	0.038
Mercury	mg/l	0.0022	0.001	0.001	0.0009	<0.0003	0.0001	<0.0003	<0.0001
Arsenic	mg/l	<0.01	<0.004	<0.01	<0.005	0.012	<0.007	<0.005	<0.001
Lead	mg/l	0.40	0.24	0.33	0.25	0.38	0.13	0.55	0.14
Zinc	mg/l	0.13	0.08	0.14	0.09	0.20	0.13	0.25	0.22
Iron	mg/l	7.67	3.30	6.13	3.47	30.8	8.52	29.2	5.88
Copper	mg/l	0.12	0.08	0.14	0.11	0.15	0.14	0.05	0.04
Nickel	mg/l	0.03	0.021	0.07	0.061	0.15	0.08	0.08	0.05
Chromium	mg/l	0.07	0.061	0.08	0.07	0.19	0.06	0.12	0.03
Cadmium	mg/l	<0.01	<0.004	<0.01	<0.005	<0.01	<0.003	<0.01	<0.002

* Concentrations given here assume pollutants are uniformly distributed between settleable and non-settleable suspended solids.

The results of the lime stabilization tests for the October 25, 1980 swirl/helical bend samples are similar to those for the Racine samples (Table 15). As the concentration of solids increased the concentration of lime required for stabilization also increased. However, the quantity of lime based on volume treated is significantly less for the thickened residuals due to the separation of water and its associated lime demand.

Results of the capillary suction time tests are presented in Table 16. The increase in the capillary suction time (CST) of the thickened residuals over the unthickened residuals is due to the thickened solids increased affinity for water. Thus the water is withdrawn at a slower rate by the test pads. Unthickened residuals with their relatively low solids concentration cannot produce a significant enough force to slow the movement of water into the filter pad. In the October, 1980 samples the thickened residuals CST's were at least five times greater than the unthickened residuals CST's, while the June, 1981 samples were only 2.6 and 3.3 times greater.

The results of these treatability tests show that gravity thickening and centrifugation are effective methods for concentrating stormwater runoff residuals. A solids recovery between 46 percent and 94 percent with sedimentation and between 82 percent and 99 percent with centrifugation shows that these systems will significantly thicken urban residuals for further handling and disposal. Based on these results an analysis of the cost effectiveness of each system will be presented in the next section.

SECTION 7

COST EVALUATION FOR HANDLING AND DISPOSAL OF URBAN RUNOFF RESIDUALS

The objective of this section is to present an evaluation of the costs associated with the handling and disposal of urban stormwater runoff residuals. The cost data for this section were obtained from the 1978 Dodge Manual for Building Construction Pricing and Scheduling and various equipment vendors (prices were adjusted to 1981 dollars). Design criteria for the residuals handling and disposal systems to be presented in this section are based on data from characterization analyses (Section 5) and treatability tests (Section 6). All assumptions will also be included in the discussion of the costs of each treatment system evaluated. Finally, it was not within the scope of this project to consider urban runoff treatment, but rather only the residuals generated therefrom. For the purposes of this section, however, some general assumptions had to be made concerning runoff treatment.

Before beginning a discussion of the cost evaluation of urban stormwater runoff residuals handling and disposal systems, a review of the criteria used to determine which systems may be feasible will be presented. The most important criteria to be considered are the intermittent nature of urban stormwater runoff, the relatively short duration of the runoff, and the volume of runoff from each event that will be treated. Many conventional wastewater treatment systems are available, but these systems are usually utilized at facilities that process a relatively constant flow, and are continuously operated. They treat a large volume of wastewater, but the load is spread over an extended period of time. To use conventional treatment processes such as chemical flocculation or multi-media filters would require large expensive facilities operated only on an intermittent schedule. Thus to effectively treat urban stormwater runoff residuals (in terms of costs and quality of stormwater discharge to receiving waters) a facility with a small capital investment and low operation and maintenance costs is required. The characteristics of the urban stormwater runoff residuals also preclude the use of conventional biological treatment facilities. Low organic content (11 to 88 mg/l BOD_5 in the Racine and Boston samples) would eliminate the waste activated sludge process, trickling filters, anaerobic digestion or any other biological processes from being considered as potential residuals treatment systems.

The two techniques which have been considered in the treatability study to concentrate stormwater residuals, gravity thickening and centrifugation,

have previously been shown to be effective for treating sludges from combined sewer overflows. Gravity thickening of CSO from 0.2 percent solids to 1.33 percent solids with the aid of ferric chloride and polymer was observed (19). Bench scale tests using a basket centrifuge showed that degritted and thickened sludge could be dewatered to 28 percent solids. Chemical addition was required to concentrate combined sewer overflow solids because of a significant amount of dispersed organic solids. Dispersed organic solids were not present in significant concentrations in the supernatant of settled urban stormwater runoff residuals, and based on the results of the treatability tests in Section 6, it appears that no chemicals would be required during the dewatering of urban stormwater runoff residuals.

Centrifugation, which gave good results on CSO sludges does not appear to provide advantages which are significant enough to include it as a residuals thickening step for stormwater runoff residuals. The capital and maintenance costs required for a centrifuge that will dewater the gritty and abrasive materials present in the residuals were felt to be excessive in light of the treatability data presented. It is a recognized fact that gritty and abrasive type solids cause serious maintenance problems when processed in high speed centrifuges. Estimates of cake solids concentrations from centrifuged urban stormwater residuals were between 10 and 14 percent, while gravity thickening of the same residuals produced solids concentrations of between 9 and 19 percent. (These data are for residuals samples from Racine and Boston). Centrifugation undoubtedly has a higher solids capture rate and the centrate suspended solids concentration is less than the suspended solids concentration in the supernatant from the gravity thickening tests, but again these advantages were felt to be minor compared to the added costs.

It will be assumed here that one type of sedimentation/storage system will be used to treat urban runoff and produce thickened residuals at a 10 percent total solids concentration. The cost evaluation to be presented here will discuss the costs associated with handling and ultimate disposal of the thickened residuals. Landfilling and lime stabilization/landspreading will be evaluated as two potential disposal options.

For the purposes of this discussion it will be assumed here that the stormwater runoff residuals are generated from a hypothetical drainage basin covering 50 hectares (124 acres). The thickened residuals will be collected from some type of storage/sedimentation facility that is designed to capture and treat the runoff from a one in ten year storm of sixty minutes duration. For the Milwaukee area this would be about a 5 cm (2 in.) rainfall.

Ideally, the size and number of sedimentation/storage facilities and ancillary equipment would be determined to provide the maximum treatment capacity while reducing the area of land required for the facility.

Setting aside a minimum portion of prime developed land or industrial land for an urban stormwater runoff residuals treatment facility would reduce the cost and increase public acceptance of the project. When these facilities are located in residential areas, extra attention would also have to be given to the site aesthetics.

Stormwater runoff treatment facilities in most areas of the country would be unused for extended periods of time; for example, in those areas of the country which have little or no runoff during the winter months. Treatment facilities in these locations should be designed to shutdown for the duration of this period with a minimum of maintenance, and likewise be put back on line with a minimum of maintenance. The design of these facilities could be compared to the design of emergency or back-up systems, in that they operate for relative short durations (usually during adverse conditions such as storms), and remain idle for the remainder of the time.

No specific land use will be given for the hypothetical drainage basin and it will be assumed that the stormwater runoff residuals from the basin are similar to those residuals from the Racine and Boston sites. The runoff coefficient for the drainage basin will be assumed to be 0.5. The volume of runoff from this area would then be 12,700 m^3 (3,355,000 gal.) for the one in ten year storm of one hour duration.

The evaluation of the two potential residuals handling and disposal treatment systems is presented below. Schematic diagrams of each treatment system are presented in Figures 15 and 16 along with assumptions related to system performance. Other general assumptions employed for the subsequent cost comparisons are summarized in Table 19. The volume of residuals that will require handling and disposal will obviously vary from storm to storm. If the rain occurs at the end of a prolonged dry spell the quantity of residuals present in the runoff will undoubtedly be greater than those found in a similar storm that occurs after only a few antecedent dry days. For the hypothetical system presented here it will be assumed that the stormwater runoff will have a suspended solids concentration of 300 mg/l and that approximately 75 percent of these suspended solids will be collected as residuals. The stormwater runoff suspended solids concentration was determined after a review of data presented in Table 3 and by Lager and Smith (1). Assuming the thickened residuals have a total solids concentration of 10 percent (see Table 11) then the quantity of dry residuals produced by the hypothetical system presented above is rounded off to approximately 3000 kg (6,600 lb). Assuming 10 percent solids, the mass of the wet residuals is 30,000 kg (66,000 lb) and the wet residuals volume is rounded off to approximately 30 m^3 (8,000 gal.) which are to be used as starting values in the cost evaluation discussion. This is the quantity of residuals that require further handling and disposal. For the purposes of this analysis, it is assumed that the supernatant from the thickened stormwater residuals will be discharged into a storm sewer, though in an actual situation, an assessment would have to be made of the impact of such a discharge.

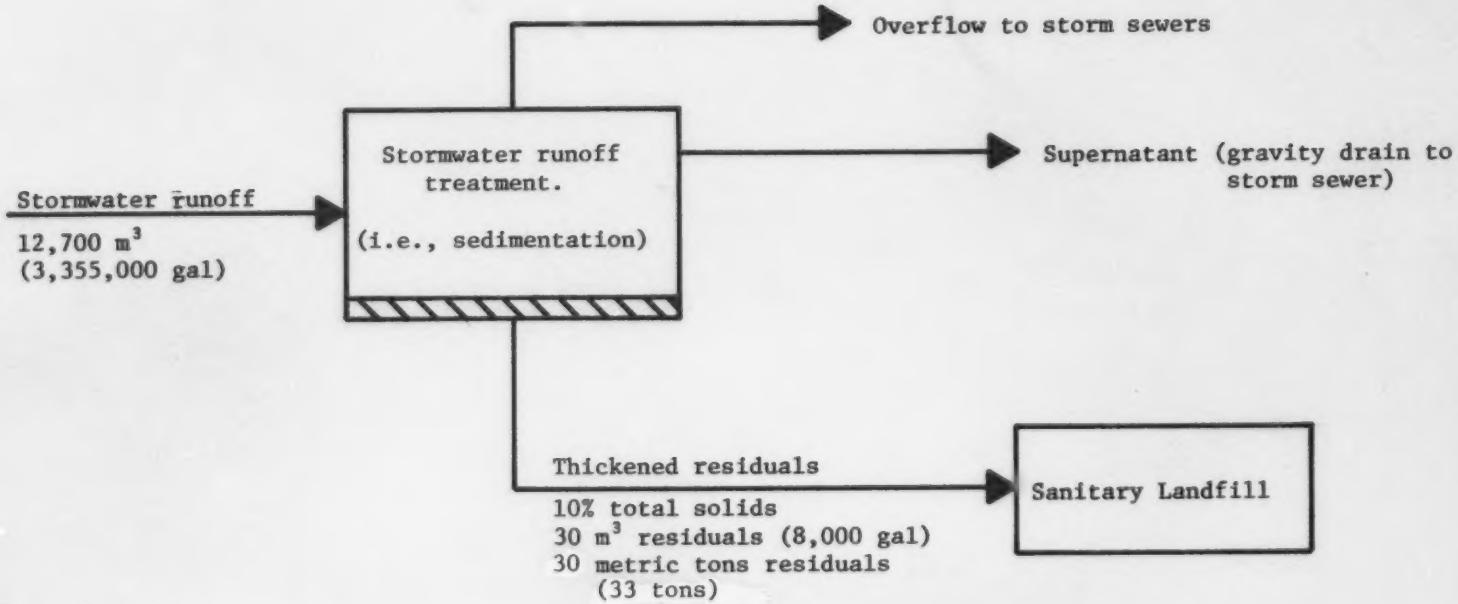


Figure 15. Schematic diagram of stormwater runoff residuals handling and disposal system (landfill option).

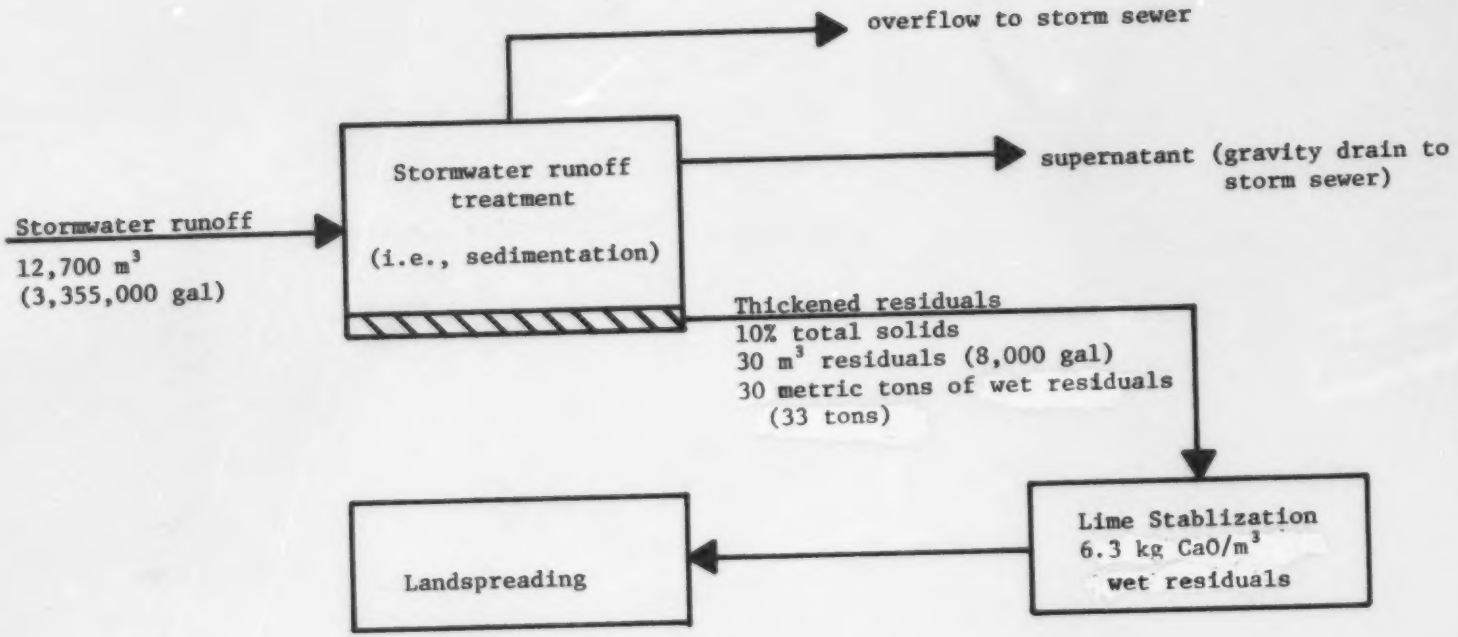


Figure 16. Schematic diagram of stormwater runoff residuals handling and disposal system (landspreading option).

TABLE 19. ASSUMPTIONS FOR COST EVALUATION OF URBAN STORMWATER RUNOFF RESIDUALS HANDLING AND DISPOSAL SYSTEMS

Residuals are produced at the rate of 30 m^3 per 5 cm of rainfall
A maximum of 24 hours required to pump or convey residuals from storage/ sedimentation facility
Cost of residuals conveyance system includes installation
Power costs are $0.06/KWH
Maintenance costs are 10 percent of total capital costs
Engineering and contingency costs are 25 percent of total capital costs
Facility operates for 50 days a year
Facility has worker on site for 16 hours of each day system is operating
Labor costs are $8/hour
Wet residuals landfilling costs are $19.60/$m^3$ ($15/$yd^3$) and includes a round trip hauling distance of 30 miles
An average rainfall of 76 cm (30 in.) per year is assumed for cost requirement
Lime costs are $22 per metric ton
Landspreading costs include operator wages and equipment costs [$15/$m^3$ ($11.50/$yd^3$)]. This cost estimate does not include leasing land or transferring residuals to a second vehicle for spreading.

Table 20 presents the cost summary for the landfilling disposal option presented in Figure 15. The cost data presented in Table 20 are only for the residuals handling (removing thickened residuals from storage facility) and disposal (hauling and landfilling). The cost of the urban runoff treatment system used to thicken the stormwater residuals is not presented here. The total annual cost for the landfilling option includes operation, maintenance, and capital costs.

The cost data for the landspreading option is presented in Table 21. The additional costs required for landspreading includes equipment and chemicals for lime stabilization (pathogens in the residuals should be destroyed before surface land application). A lime metering device and a mixing system are required to stabilize the thickened residuals. Since the fertilizer and soil conditioning value of the thickened residuals is minimal (phosphorous and nitrogen levels well under one percent of the total solids - see Figure 10) there is a possibility that land may have to be leased for spreading residuals. If such were the case, the cost of leasing the necessary land would have to be added to the estimate cost presented herein. The estimated total annual cost of the landspreading option presented in Figure 16 is $23,400. This estimated cost includes amortized capital cost, lime, operation, maintenance, power, and residuals hauling and landspreading (see Table 21). The cost estimate for residuals landspreading assumes that the same vehicle that collects the residuals from the treatment facility also spreads the material on the land. However, many variables may affect this cost estimate ($15 per m^3 of wet residuals) for landspreading urban runoff residuals. If the site accessibility is limited and/or the leased land cannot bear the load of a large truck then the residuals will have to be transferred to a second vehicle for spreading. This situation would increase the landspreading cost. If land must be leased for spreading then the annual cost will increase accordingly. Also if sites are limited and factors such as surface runoff and groundwater contamination have to be considered then appropriate measures to mitigate any potential adverse impact will have to be implemented and this will probably increase costs. Another factor which may affect the cost of residuals disposal is regulations governing the application of waste containing hazardous materials to land. Also if there is any chance the land that is currently accepting residuals will ever be used to grow crops or support livestock then load limits on the hazardous components of the residuals will allow only a given amount of residuals to be applied. Thus new landspreading sites will have to be located periodically. All of the above contingencies will most likely increase the cost of landspreading and therefore, make other disposal options such as landfilling more viable alternatives.

A comparison of the total annual cost for each option shows landfilling to be $18,020 while landspreading is $23,400 for the hypothetical 50 hectare site. The higher landspreading cost is due primarily to increased capital costs for lime stabilization equipment, lime costs, and maintenance costs. The item cost of landfilling is slightly greater than the landspreading item cost ($9,000 per year vs. $7,500)

TABLE 20. COST* SUMMARY FOR THE STORMWATER RUNOFF RESIDUALS HANDLING AND DISPOSAL SYSTEM PRESENTED IN FIGURE 15 (Cost summary does not include costs for stormwater runoff treatment facility).

Residuals conveyance system[a]	$10,000
Engineering and contingency costs (25%)	2,500
Total capital costs	$12,500
Amortized capital cost (20 yr/8%)[b]	$1,270
Operation (50 day/year)	6,400
Maintenance (10%)	1,250
Power ($0.06/KWH)	100
Wet residuals hauling and landfilling ($19.60/$m^3$)[c]	9,000
Total annual costs	$18,020

*Costs are in 1981 dollars - refer to Table 19 for cost estimate assumptions.

[a]The method used to convey residuals from the storage facility to hauling vehicle will depend on the nature of thickened residuals. Pumps used in this case though a screw conveyor is a possible alternative.

[b]Cost of equipment and construction of facilities for handling runoff residuals. Land costs are not included.

[c]Hauling costs are based on collecting 450 m^3 of wet residuals from 76.2 cm (30 in.) of rainfall per year. Disposal costs based on a tipping fee at a licensed disposal site. Hence land purchase not included.

TABLE 21. COST* SUMMARY FOR THE STORMWATER RUNOFF RESIDUALS HANDLING AND DISPOSAL SYSTEM PRESENTED IN FIGURE 16. (Cost summary does not include costs for stormwater runoff treatment facility).

Lime stabilization	
Residuals conveyance system[a]	$10,000
Building for lime storage and mixer	12,500
Lime feeder	5,500
Lime/residuals mixer	5,000
Engineering and contingency costs (25%)	8,300
Total capital costs	$41,300
Amortized capital costs (20 yr/8%)[b]	4,200
Lime costs (3 metric tons CaO)	900
Operation (50 days/year)	6,400
Maintenance (10%)	4,100
Power ($0.06/KWH)	300
Wet residuals hauling and spreading[c] ($15/$m^3$)	7,500
Total annual costs	$23,400

*Costs are given in 1981 dollars - refer to Table 19 for cost estimate assumptions.

[a]The method used to convey residuals from the storage facility to lime mixer and hauling vehicle will depend on the nature of the thickened residuals. Pumps used in this case, though a screw conveyor is a possible alternative.

[b]Cost of equipment and construction of facilities for handling runoff residuals. Land costs are not included.

[c]Contingencies on this value are discussed in the text. Land purchase not included.

but the difference could be less if any of the contingencies discussed above are applicable.

The assumptions used in the cost calculation are presented in Table 19 presented previously. A comparison of the cost data presented above is given in Table 22. Included are annual costs on a per hectare, per metric ton dry residuals, and per cubic meter of wet residuals basis.

The cost data presented in this section provide an estimate of the annual cost that may be expected when one undertakes the disposal of urban stormwater runoff residuals. The two disposal options, landfilling and landspreading, are probably the most efficient and cost effective methods for disposing of thickened stormwater residuals. Some contingencies and the resulting impacts on the cost and performance of each disposal system have been presented, but these contingencies should in no way be considered all inclusive. Variations in drainage basins, stormwater runoff residuals, and disposal options will probably be significant from site to site and thus a comprehensive review of each site must be completed before implementing a particular option. This research project will hopefully provide a framework on which to analyze the needs of any given locality, as it initiates the task of determining the most effective method for handling and disposing of urban stormwater runoff residuals.

TABLE 22. SUMMARY OF COST* DATA FROM TABLES 20 AND 21
(COST OF RESIDUALS MANAGEMENT FOR HYPOTHETICAL 50 HECTARE SITE)

	Table 20 Landfill	Table 21 Landspreading
Total capital costs	$12,500	$41,300
Amortized capital cost (20 years/8% interest)	1,270	4,200
Annual operation and maintenance cost	16,750	19,200
Total annual cost	18,020	23,400
Annual cost per hectare	360	470
Annual cost per metric ton dry residuals	400	520
Annual cost per m^3 of wet residuals	40	52

*Cost data are in 1981 dollars.

SECTION 8

PROJECT SUMMARY

The goals of this research project were to characterize residuals generated from treatment of urban runoff and determine the most feasible and cost effective method(s) for handling and disposing of these residuals.

Data gathered from treatment systems at Racine, WI and Boston, MA show that stormwater residuals can be expected to be of low total solids concentration with a significant fraction of the solids present as suspended solids. In this study the total solids concentration ranged from 230 mg/l to 1,140 mg/l while the suspended solids fraction varied from 53 to 96 percent of the total solids. These residuals have been shown to readily settle and as a result sedimentation should be expected to reduce significantly the pollutional impact of the stormwater runoff on receiving waters. Characterization data also showed that in most cases a significant fraction of heavy metals, pesticides, nutrients and oxygen demanding materials were associated with the suspended solids.

The stormwater runoff residuals analyzed in this study were from both combined and separate runoff events, from three different sites and from four different treatment processes. It would be risky at best to assume the results of this study could be applied to any runoff event anywhere in the country. This study did not attempt to investigate the impact of land use, rainfall intensity, or antecedent dry days on stormwater residuals characteristics and treatability. Yet, all three of these factors influence the quantity and type of residuals that will be present in stormwater runoff. What was accomplished in this study was the establishment of suggested design parameters that must be considered when designing a facility for the treatment of stormwater runoff residuals from urban areas. Examples are the range of particle settling velocities, the impact of centrifugation on centrate solids concentration and cake solid concentrations, the quantity of lime required for stabilization, the concentration of residuals that can be expected from sedimentation, and levels of pollutant reduction that can be expected from removing residuals from stormwater runoff.

The two sludge handling and disposal systems reviewed in Section 7 were evaluated to determine their cost associated with treating urban runoff residuals. These systems were designed for a hypothetical drainage basin, and are not presented as the only options available for treating urban runoff residuals. Each drainage basin must be studied separately to determine the most feasible treatment method.

SECTION 9

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APPENDIX A

ANALYTICAL PROCEDURES

The following analyses were performed according to Standard Methods for the Examination of Water and Wastewater, 14th Edition, 1975 (SM) or Methods for Chemical Analysis of Water and Wastes, 1979 (EPA).

Parameter	Reference	Technique	Page
Total solids	SM	208A	91
Volatile total solids	SM	208E	95
Suspended solids	SM	208D	94
Volatile suspended solids	SM	208B	96
Total dissolved solid	SM	208B	92
BOD_5	SM	507	543
Total organic carbon	SM	505	532
COD	SM	508	550
Total phosphorous	SM	425	466
Total Kjeldahl nitrogen	SM	421	437
NH_3	SM	418D	417
Nitrage/nitrite	EPA	353.2	
Oil and grease	EPA	413.1	
Metals (Zn, Pb, Cu, Ni, Cr, Cd, Fe)	EPA	4.1.3 (Perkin Elmer Model 560 Atomic Absorption Spectrometer)	Metals -6
Arsenic	SM	404A	283
Mercury	SM	301A-VI (Perkin Elmer Model 403 Atomic Absorption Spectrometer)	156
Pesticide and PCBs		Details of the pesticide analytical procedure are included later in the appendix	
Soluble parameters		Samples were filtered through 0.45 μ membrane filters to remove suspended solids. Soluble sample for pesticides and PCB's were obtained by centrifuging at 3000 rpm for 10 minutes	

PESTICIDE ANALYSIS

Introduction

The method described here was used for the extraction and isolation of organochlorine pesticides and certain polychlorinated biphenyls (PCB) from stormwater and combined sewer overflow sludges. This method is based on EPA approved procedures. The following organochlorine pesticides were measured; lindane, aldrin, dieldrin, endrin, DDE, DDD, DDT and methoxychlor.

The selected cleanup procedures permitted the analyst to eliminate certain anticipated interferences and allowed for separation of analogs of Archlor no. 1254 and 1242 from organochlorine pesticide.

Summary

PCB's and organochlorine pesticides were coextracted either by liquid-liquid extraction or for samples of high solids by mixing with anhydrous Na_2SO_4 and soxhlet extraction. A combination of the standard Florisil column cleanup and silicic acid column chromatography were employed to separate PCB's from organochlorine pesticides. Identification was made with a gas chromatograph equipped with an electron capture detector through the use of two or more unlike columns.

Interferences

All glassware, solvents, reagents, and sampling hardware must be demonstrated to be free of interferences under the conditions of analysis. Therefore, all glassware was fired at 230°C.

Apparatus

1. Gas chromatograph equipped with integrater
2. Detector, electron capture
3. Gas chromatograph columns
   Two unlike columns of non-polar and semipolar type suitable for pesticide analysis (e.g., glass 1/4" x 6 ft packed with 1.5 percent, SP2250/1.95 percent SP2401 on 100/120 supelcoport: 5 percent SP2401 on 100/120 supelcoport.
4. 500 ml Kuderma-Denish glassware (Kontes K-570000)
5. Chromatographic column 400 x 22 mm (Kontes K-420550, C-4) with adapter, hose connector type (Kontes K-185030)
6. Separating funnel 250 ml (Kontes K-633030)
7. Evaporative concentration (Kontes K-569250)
8. Concentrator tube (Kontes K-570050) graduated in 0.1 ml to 1 ml
9. Separatory funnels (125 ml, 1000 ml with Teflon stopcocks)
10. Volumetric flask 250 ml
11. Florisil-PR Grade (60 to 100 mesh) prepared after the method of Hall (44)
12. Silicic acid, Mallickrodt 100 mesh
13. Glass wool - hexane extracted

14. Centrifuge tubes 40 ml Pyrex
15. Magnetic stirrer with teflon control bar, hexane extracted
16. 1 gallon sample bottles, with teflon caps
17. 10 ml transfer pipette
18. Celite 545 washed

Reagents, Solvents and Standards

1. Sodium sulfate ACS granular anhydrous, conditioned for 4 hrs at 400°C
2. Diethyl ether - nanograde
3. Hexane, acetonitrile, methylene chloride, petroleum ether (BR 30 to 60°C) pesticide grade
4. Standards - appropriate organochlorine and arochlors for elements in question

Sample Preparation

1. Adjusted pH to near 7.0

2. Liquid - liquid extraction was employed for samples of low solids and organic content. The procedure used for liquid-liquid extraction is described as follows:

   Place an aliquot of the sample in a two liter separatory funnel. Add 60 ml of 15 percent methylene chloride in hexane (V:V) and shake vigorously for two minutes. Allow the phases to separate and drain the water layer into a clean Erlenmeyer flask. Pass the organic layer through a 3 to 4 inch column of anhydrous Na_2SO_4 and collect in a 500 ml K-D flask. Return the water phase to the separatory funnel and rinse the Erlenmeyer with a second 60 ml volume of solvent. Add the solvent to the separatory funnel and complete the extraction procedure. The water phase should be extracted with three 60 ml aliquots of solvent. Concentrate the extract on a water bath to 5 ml.

3. The concentrate was analyzed quantitatively to determine:

   a. If organochlorine pesticides were present
   b. If PCB's were present
   c. Combination of a and b
   d. If elemental sulfur was present.

4. If a, determined organochlorine pesticides

5. If b, determined PCB's

6. If c, compared peaks obtained to standard arochlors and determined which Arochlors were present. If Arochlor peaks were analogs of no. 1254 and no. 1242, the PCB's were separated from DDT and its analogs by the combination of Florisil column and silicic acid column technique.

7. If d, remove sulfur.

Cleanup and Separation Procedures

1. Florisil column cleanup - Place a charge of activated Florisil [the weight of the charge is determined by its Lauric Acid Value, see Hall (51)] in the Chromaflex column and settle by gentle tapping. Add a 1 cm layer of anhydrous sodium sulfate and pass 50 to 60 ml of petroleum ether through the column. When the petroleum ether is about 5 mm from the sodium sulfate, transfer the sample extract by decantation and petroleum ether washings to the column and elute with the following mixed ethers at 5 ml/minute. (NOTE: For both column chromatography procedures the elution rate is important. To quickly adjust this rate the lower part of a broken 25 ml burette equipped with teflon stopcock placed between the chromaflex column and the receiving vessel is most useful in making repetitive low adjustments without losing eluate.) Collect each eluate in a 500 ml K-D flask.

   To the first elution (6 percent eluate) add 200 ml of 6 percent ethyl ether in petroleum (V/V); second elution, 200 ml 15 percent ethyl ether in petroleum either. Most pesticides of interest will be in these eluates.

6 percent Eluate
Aldrin
DDD
DDE
DDT
Lindane
Methoxychlor
PCB's

15 percent Eluate
Endrin
Dieldrin

   Concentrate the eluates and analyze by GLC.

2. Silicic acid column separation procedure

   A. Silicic acid preparation

      a. Celite 545 must be oven dried and free of electron capturing substances (acid washed).

      b. Silicic acid - Oven dry for a minimum of seven hours at 130°C to remove water. Cool the silicic acid and weigh into a glass stopper bottle and add 3 percent water. Stopper bottle and shake well. Allow 15 hours

for equilibrium to occur. Determine separation achieved by loading 40 µg of Arochlor no. 1254 and pp 'DDT in hexane on the column. Inadequate separation will mean readjustment of the water content of the silicic acid in recommended increments of 0.5 percent. More water is required when the PCB elutes in the polar solvent with pp 'DDE; less water when pp 'DDE elutes in the petroleum ether portion. Standardization is required for each new lot of silicic acid purchased. Once a batch of silicic acid is hydrated activity remains for about 5 days.

B. Column preparation - weigh 5 g of celite and 20 g of silicic acid and combine in a 250 ml beaker. Immediately slurry with 80 ml of petroleum ether. Transfer the slurry to the chromatographic column, keeping the stopcock open. Stir the slurry in the column to remove air bubbles, then apply air pressure to form the petroleum ether through the column. Do not allow the column to crack or go dry and close the stopcock when air pressure is not being applied. Stop the flow when the petroleum ether level is 3 mm above the surface of the silicic acid. The adsorbent at this point should be firm and not loose shape if tapped.

C. Elution patterns - Large amounts of PCB's or pesticides placed on the column will result in incomplete separation. The extracted sample placed on the column should contain no polar solvents and be $\leq$5 ml in volume. Place a 250 ml volumetric flask beneath the column and carefully add a suitable aliquot of the 6 percent florisil eluate, taking care not to disturb the surface of the silicic acid. Apply slight air pressure until the solvent level is each 3 mm from the surface of the silicic acid. Carefully position the 250 ml separatory funnel containing 250 ml of petroleum ether on the column and allow the petroleum ether to run down the sides of the column until the space above the silicic acid is one half full. Apply air pressure and adjust the flow rate to 5 ml/minute. When exactly 250 ml are collected, replace the volumetric flask with a 500 ml K-D flask and elute at 5 ml/min with 200 ml of methylene chloride, hexane and acetonitrile (80:19:1, V/V) to recover the pesticides. Quantitatively transfer the petroleum ether eluate containing the PCB's to a 500 ml K-D and concentrate both eluates to 5 ml. Analyze via GLC. NOTE: the separation between the PCB's and pp 'DDE is very narrow; great care should be exercised in adjusting the elution flow rate and volume of the petroleum ether portion.

Petroleum Ether Eluate

Aldrin
Arochlors no. 1254 no. 1242

Polar eluate (acetonitrile, methylene chloride, hexane)

a. These Arochlors divide between the two eluates. The earliest eluating peaks may occur in the polar eluate.

D. Confirmation techniques - Qualitative confirmation by comparing relative retention time (RRT) of the constituents on two or more unlike columns is suggested as a minimum criteria for identification after appropriate cleanup and column chromatography.

If an Arochlor analog which does not completely occur in the petroleum ether eluate is suspected, the alkali-de-chlorination procedure is strongly recommended. In any event such confirmational techniques add greatly to the reliability of the residue analysis in the absence of more sophisticated mass spectroscopy instrumentation.

APPENDIX B

BENCH SCALE TEST METHODS

GRAVITY THICKENING

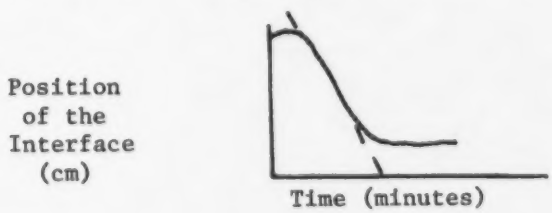
The bench scale tests described herein were used to determine whether the residuals were amenable to thickening by gravity sedimentation.

Procedure

1. Obtain a representative sample of the residuals.
2. Use a portion of the sample for suspended and total solids analyses.
3. Measure and record in centimeters the distance between the zero ml and 1,000 ml marks on a 1 liter graduated cylinder.
4. Fill the cylinder with residuals to the 1,000 ml mark.
5. Start the stopwatch.
6. Record the position of the interface (in cm) with respect to time (in minutes). Continue recording at 2-10 min. intervals (or more frequently if necessary) for 2 hours or until no further settling or compaction occurs.

Data Analysis

1. Plot the data obtained from the settling tests, i.e. position of the interface in centimeters versus time in minutes. Each graph will have the following configuration:



The settling rate is the linear portion of the curve. Determine the settling rate in cm/min and convert to any other convenient units if desired.

CENTRIFUGE TEST PROCEDURE

The purpose of this test is to determine the dewatering characteristics of residuals by centrifugation. Data obtained include the effects of centrifugal force, the effect of residence time, estimates of solids recovery, and sludge concentration.

Procedure

Approximately 2-4 liters of residuals are required to run a complete test series. If the residual contains large or stringy materials, it should be prescreened on a coarse screen to avoid erroneous results.

1. Mix the screened residuals well and obtain a sample.

2. Place 45 ml of residuals into each of the centrifuge tubes. NOTE: It is important that balanced amounts of samples be placed in opposite centrifuge tubes. Sample sizes other than 45 ml may be used, but the amount must be the same in opposing centrifuge tubes.

3. Place in the centrifuge and spin for a predetermined time at the required centrifugal force. Suggestions for spin time are 30 seconds and 90 seconds. Suggested centrifugal forces are 400 g, 800 g, and 1200 g. The step by step procedure for this test using the Spruall (manufacturer of the centrifuge) Model GLC-2 centrifuge is as follows:

    a. Place the filled centrifuge tubes in the head.

    b. Turn the timer dial clockwise to the"hold" setting.

    c. Determine the rpm required to obtain the desired centrifugal force for the centrifuge tubes used.

    d. From the centrifuge calibration curve, determine the setting on the speed control which will yield the required rpm with the number of centrifuge tubes used.

    e. Close and lock the centrifuge cover.

f. Quickly turn the speed control knob clockwise to the required setting simultaneously starting the stopwatch.

g. At the end of the predetermined spin time, turn the speed control knob counter-clockwise to zero and immediately apply the brake until the head stops.

4. Record the cake volume on a data sheet.

5. Pour off the centrate from the tubes into a graduated cylinder. Record the centrate appearance and the total volume. Mix well and obtain a sample of the centrate.

6. Repeat steps 2 through 5 for all test conditions.

Data Analysis

Estimate the percent solids recovery for each test utilizing the following equation:

$$\% \text{ Recovery} = \frac{C_f - C_c \times 100}{C_f}$$

where C_f = suspended solids concentration in the feed residuals (mg/l)

C_c = suspended solids concentration in the centrate (mg/l)

VACUUM FILTRATION TESTS

Buchner Funnel Test Procedure (For Lansing, MI sample)

1. Moisten filter paper (Whatman #4 and place it in the Buchner Funnel. Apply a vacuum to obtain a seal. Empty water collected in filtrate receiver.

2. Analyze the residuals to be filtered for solids content.

3. Measure a volume of residual that will provide a 3 mm to 6 mm thick cake.

4. Add the residuals to the funnel and quickly apply vacuum. As soon as vacuum is applied, start the stopwatch. A vacuum reservoir may be needed to hold a constant vacuum.

5. Take filtrate volume readings with respect to time.

6. Continue the test until the cake cracks, or no filtrate is deposited for a one minute interval. Usually five minutes is sufficient. Be sure the cake edges do not shrink from the sides of the Buchner funnel. If it does, tap the edges of the cake to maintain a seal.

7. Sample cake for total solids.

8. Record filtrate temperature, vacuum level, and cake thickness.

9. Plot a curve of time/volume filtrate vs. volume filtrate and record the slope of the curve. The slope recorded should include only the linear portion of the curve.

$$a = 2PA^2b/\mu\omega$$

where a = specific resistance in sec^2/gm
p = vacuum level in gm/sq cm
A = area of Buchner funnel in sq cm
b = slope of t/v vs. v curve in sec/cm^6
μ = viscosity in Poise
$\omega = 1/[Ci/(100-Ci)) - Cf/(100-Cf))]$

Ci = initial residual moisture (%)
Cf - moisture concentration in cake (%)

SETTLEABLE SOLIDS

Settable solids may be determined and reported on either a volume basis (milliliters per liter) or a weight (milligrams per liter) basis. (See Method 208F in reference 12.)

Procedure

By volume:

1. Fill Imhoff cone to one liter mark with well mixed sample.

2. Settle for 45 minutes, then spin cone gently. Settle for 15 minutes more.

3. Record volume of settleable matter in the cone as milliliters per liter.

By weight:

1. Determine suspended solids of well mixed sample.

2. Pour sample in glass vessel not less than 9 cm in diameter. Let stand quiescent for 1 hour.

3. Siphon 250 ml from center of container at a point halfway between the settled sludge and the liquid surface.

4. Determine the suspended solids in the supernatant. This is the